# Energy Efficiency and Integration in the Refining and Petrochemical Industries

THÈSE N$^{O}$ 7038 (2016)

PRÉSENTÉE LE 1$^{ER}$ JUILLET 2016

À LA FACULTÉ DES SCIENCES ET TECHNIQUES DE L'INGÉNIEUR
LABORATOIRE D'ÉNERGÉTIQUE INDUSTRIELLE
PROGRAMME DOCTORAL EN ENERGIE

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

POUR L'OBTENTION DU GRADE DE DOCTEUR ÈS SCIENCES

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ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

Suisse
2016

What if it’s a big hoax and we create a better world for nothing ?
— Joel Pett

Good judgement comes from experience, and experience comes from bad judgement.
— Frederick P. Brooks

# Acknowledgements

*This work brings to an end more than a decade spent at EPFL. There are many people whom I would like to thank for accompanying me on this journey, know you are in my heart.*

*Ce travail conclut plus de dix ans passés à l'EPFL. Nombreuses sont les personnes que j'aimerais remercier de m'avoir accompagné sur ce voyage, sachez que vous avez un place dans mon cœur.*

I would firstly like to thank my thesis supervisors Professors Greet Van Eetvelde and François Maréchal. Greet, thank you for creating the opportunity to do so much interesting work and for your support throughout these four years. You have truly offered me a challenging working environment as well as the space to increase my knowledge and explore the field.

François, thank you for providing a limitless resource of unimaginably innovative ideas and for continued support over the past six years. The spirit that you have successfully created in your laboratory has helped foster the ideas that have become this work. The balance between supervision, guidance and autonomy that you have offered are what made my accomplishments possible.

My thanks also go to my thesis jury, Professors Konrad Hungerbüler, Zdravko Kravanja, Christophe Ballif and Dr Bernard Descales.

I am particularly appreciative of the possibilities that INEOS has offered me over these past four years, giving me access to its industrial sites, data, resources, trainings and employees.

Aux Français d'INEOS, je n'oublierais pas le cadre que vous m'avez offert à Lavéra. A Bernard Descales, j'aimerais dire un grand merci pour ton support continu, les discussions et l'introduction à Marseille.

A Jean-Noël Large, tes pistons, contacts et infos sur la raffinerie m'ont été incontestablement utiles, j'ai beaucoup apprécié ton amabilité et jovialité.

A Bob Nater, merci de ta patience lors de mes premiers jours à Lavéra.

A Lionel Pasquinucci et Jérôme Audibert, avec qui j'ai partagé un bureau, vous avez pour toujours gravé en moi une image très positive du Sud, et je ne pense pas pouvoir un jour trouver une meilleure alternative à la pause midi que celle que vous m'avez offerte. En plus, j'ai trouvé en vous deux sources d'informations et de conseils qui m'ont été plus qu'utile à travers le temps.

A l'équipe du CTL, Laurent Caranoni, Nicolas Vanhecke, David Blanco, Michelle Wu-Yu, Laurence Serpolet et les autres, votre amitié et disponibilité ne seront pas oubliés, merci pour tout.

J'aimerais aussi remercier Daniel Rondelez, Joelle Collomb, Jean-Louis Chamayou, Xavier Blanchard et Hugues de Montessus pour votre soutien ainsi que de m'avoir ouvert les portes du site.

I would like to thank Stefan Krämer and Ralf Gesthuisen who showed Elfie Méchaussie and I the Köln site and its surroundings, heartily and with friendliness. You've set for me a very high standard to reach as engineers and managers and I thoroughly enjoyed being in your presence.

My gratitude also goes to John McNally, Pete Williams and Carl Vercauteren who have enabled this work and followed from afar.

This work would not have been possible without the students who contributed to it. Lorenz Kausche, Erik Ringvold, Hélène Cervo, Claude Muller, Hür Bütün, I learned a lot through and because of you. Your stimulating questions served as my greatest source of inspiration, and I honestly believe the quality of your work surpassed mine. I wish you all the best.

I was fortunate enough to collaborate with a great researcher and very excellent person, Roman Hackl. A phone call is all it takes apparently. Repeatedly meeting his director, Professor Simon Harvey and colleagues from the Chalmers University of Technology also proved to be a most enjoyable experience.

A PhD is not necessarily carried out within a team, though without the team and colleagues it would not be the same. The LENI, IPESE and FUELMAT groups have served as a welcomed source of colleagues, support, camaraderie and friendship. Being able to count on you has made my life easier on countless occasions and I am very grateful for all you've contributed to my work and lab experience.

Un grand merci à l'équipe administrative du laboratoire ; Sylvie Dubuis, Brigitte Fayette et Irène Laroche, sans vous rien ne marcherait !

To Samira Fazlollahi who introduced me to the laboratory and the field, I greatly enjoyed working with you and learned a lot from it. It would surely have been a different journey without your help, guidance and support. I am forever thankful to you and hope that our paths will cross again.

I would especially like to thank those of you with whom I have become close friends over the past four years. The Climbers, the Teletravaillers and all the others, you have honestly made the entire experience so much more pleasant for me, making it exciting to come to work, although it more often felt like a summer camp. You have been likedminded individuals and have formed the basis of my support group. I have greatly enjoyed the time we've spent together.

Un remerciement spécial à Elfie, ma première étudiante et collègue préférée. L'hiver sombre de Cologne aurait été bien triste sans toi, j'ai énormément apprécié notre travail en équipe et j'espère que nos chemins se croiseront encore dans le futur.

Thank you Sophia for your generosity, Raman for your availability, Stefano for the Sunday jamming and Matthias B for your council. It would not have been the same without you guys !

Let me not forget Hussein (you impress me), Ivan, Nils (8c soon), Victor (gracias por las plantas), Jakob, Maziar, Matthias D, Leandro (LENI saviour), Jean-Loup, Nicolas (désolé pour Talc), Laurence, Alberto (censurato), Lindsey (coolest mom ever), Samuel, Araz (Biaritz again), Emanuela (incredible on a bike) and Priscilla (best Vivapoly co-organiser).

My friends have also helped make this all more joyful. You have been there with me for the ups and downs and have welcomed me in distant lands. A Lausanne je pense à Rachel, Blaz, Philipp, Georges, Vanja, Pierre, Olivier, Hamza et Manon. Honnêtement, sans vous, je n'aurais jamais terminé mon parcours à l'EPFL. Ça aurait été trop triste. A Marseille, Laura, Alex, Manu, Alice, David, Lohique, grâce à vous je m'y suis senti chez moi, et jamais seul. Quelle chance j'ai eu, de tomber sur vous. In Köln, Nicole, I am forever grateful to you and you know why. To Frank and Johnatan, I feel like we were lost together, it was nice to share that with you.

J'aimerais remercier ma famille et ceux qui m'ont suivi de très proche. À ma tante et mon oncle, Marie-Anne et Jean, merci infiniment pour tous ce que vous avez fait pour nous au fils des années, vous n'avez jamais raté un millimètre de mon progrès et avez toujours été là pour moi. Merci infiniment. Pernette, Pierre, Kathie, Mélanie, Camille, mon aventure en Suisse est meilleure grace à vous.

Katrin, you've been my ray of sunshine and my rock. If nothing came out of this thesis except for my meeting you, that would have been enough for me. Marc, Sara, this wouldn't have been possible without you, thank you for always being there for me. A mes parents, Ginette et Thierry, tout est grâce à vous et à votre soutien permanent.

I hope you enjoy the reading and thank you once again, it's been fun !

*Lausanne, 30 Avril 2016*

# Abstract

Industrial sites and their associated energy systems are estimated to be responsible for 31% of worldwide energy consumption. Improving their energy efficiencies has the potential to reduce production costs of industrial sites and contribute towards the 2050 $CO_2$ emission targets. Energy efficiency and integration studies in industrial sites aim to reduce the import of energy from external sources and maximise the use of internal energy sources, thereby reducing overall losses.

As refineries and petrochemical sites are major energy consumers and are often located close to each other, they offer substantial potential for symbiosis through Energy Integration solutions. This thesis explores the energy requirements of these two industries and the elaboration of methodologies to identify energy efficiency solutions tailored to them.

Data collection, reconciliation and preparation make up the first three chapters of this work. Typical refining and petrochemical clusters are described in detail revealing significant data issues. Data reconciliation methods are adapted to the specificities of these industries to close mass and energy balances and calculate unknowns including losses. To facilitate complex engineering studies, a methodology to identify scenarios from large data sets is proposed.

Two complementary methodologies for the generation and evaluation of Energy Integration solutions are developed in the final two chapters. Firstly Total Site Analysis is adapted to the target industries, allowing for minimal data collection through a dual representation of utility and process requirements, process stream modelling and results generation. A mathematical formulation for optimised operations of steam networks is augmented to include load shedding when operating reserves are low. This is included into a simulation of boiler failures to establish the resiliency of steam network configurations.

The data preparation methodologies, Total Site Analysis and steam network optimisation and simulation are applied to a typical refining and petrochemical cluster case study to establish energy efficiency solutions resulting in significant reduction in energy consumption.

Key words : Energy efficiency, Energy Integration, Refinery, Petrochemistry, Total Site Analysis, MILP, Steam network optimisation, Load Shedding, Boiler Failures

# Résumé


Les systèmes énergétiques de sites industriels sont responsables pour près de 31% de la consommation énergétique mondiale. L'amélioration de leur efficacité énergétique a donc le potentiel de réduire les couts de productions des sites industriels ainsi que de contribuer à la réduction d'émissions de $CO_2$ pour atteindre les objectifs de 2050 établis par les accords de la COP-21 à Paris. Les études d'efficacité énergétiques et d'intégration énergétiques ont pour but de réduire l'import d'énergie de sources externes et de maximiser l'utilisation de sources internes, réduisant les pertes des systèmes.

Les raffineries et sites pétrochimiques sont des consommateurs importants d'énergie et forment souvent des ensembles industriels étant donnée leur besoins similaires et leur possibilité de partager des ressources et réseaux d'utilitaires. Cette thèse explore la consommation énergétique de ces industries et l'élaboration de méthodologies pour générer des solutions d'efficacité énergétique adaptées à leurs besoins.

La collecte de données, leur réconciliation et leur préparation constitue les trois premiers chapitres de ce travail. Un complexe industriel comportant une raffinerie et un site pétrochimique typique sont décrits en détail, révélant des balances de masses et d'énergie ouvertes. Des outils de réconciliation de données sont adaptés aux besoins de ces industries afin de fermer les balances de masses et d'énergie et calculer les inconnues, incluant les pertes. Pour faciliter des études d'ingénierie complexes, une méthodologie est proposée pour identifier des scenarios type à partir de grandes bases de donnés.

Deux méthodes complémentaires sont ensuite proposées pour identifier des solutions d'efficacité énergétique. Premièrement la méthode du Total Site Analysis est adapté aux industries ciblés, permettant une réduction de la quantité de donnés requise grâce a une représentation double des besoins utilitaires et des procédés, ainsi que la modélisation des flux et la génération des résultats. Une formulation mathématique pour l'optimisation des opérations de réseaux de vapeurs est augmentée par l'inclusion de procédures de délestage optimales lorsque les réserves de puissance sont basses. Ces formulations sont incluses dans une simulation de panne de chaudière, pour évaluer la résilience et l'opérabilité des réseaux, ainsi que leur propositions d'investissements.

Les méthodologies pour la préparation des données, le Total Site Analyis, l'optimisation et la simulation des réseaux de vapeurs sont appliqués a un cas d'étude pour établir des solutions d'efficacité énergétique, résultant en une diminution sensible des besoin énergétiques.

Mots clefs : Efficacité énergétique, intégration énergétique, raffinage, pétrochimie, Total Site Analysis, MILP, optimisation de réseaux de vapeur, délestage, panne de chaudière.

# Contents

# Abbreviation and Symbols

| | |
|---|---|
| DA | Data Analysis |
| CB | Central Boilerhouse of the TIC |
| CC | Composite Curve |
| EMOO | Evolutionary Multi-Objective Optimisation |
| GCC | Grand Composite Curve |
| GHG | Green House Gas |
| HP | High Pressure |
| KPI | Key Performance Indicator |
| LP | Low Pressure |
| MILP | Mixed Integer Linear Programming |
| MINLP | Mixed Integer Non-Linear Programming |
| MP | Medium Pressure |
| PU | Process Unit |
| Site P | Petrochemical Site of the TIC |
| Site R | Refining Site of the TIC |
| TBP | True Boiling Point |
| TIC | Typical Industrial Cluster |
| TSA | Total Site Analysis |

**Chapter 3**

| | | |
|---|---|---|
| $F$ | | Model equalities and inequalities |
| $h_{j,inlet}$ | | Set of inlet streams of header $j$ |
| $h_{j,outlet}$ | | Set of outlet streams of header $j$ |
| $h_j$ | | Set of streams of header $j$ |
| $k_{turbine}$ | $[-]$ | Activation rate of turbine |
| $\bar{m}$ | $[t/h]$ | Mean flowrate |
| $m_{cond}$ | $[t/h]$ | Flowrate of steam condensates |
| $m_{turbine}$ | $[t/h]$ | Flowrate of steam through turbines |

| | | |
|---|---|---|
| $m_{leak}$ | $[t/h]$ | Flowrate of steam leaks |
| $n_{trap}$ | $[-]$ | Number of steam traps |
| $n_{leak,h_j}$ | $[-]$ | Number of steam leaks in header $j$ |
| $p$ | $[bar_g]$ | Pressure measure |
| $\sigma$ | $[-]$ | Accuracy of measure or estimate |
| $T$ | $[^\circ C]$ | Temperature measure |
| $y$ | | Measures or estimate value |
| $y_{forced}$ | | Cutoff value of measure |
| $y_{low}$ | | Turndown value of measure |
| $y_{max}$ | | Maximum allowable value of measure |
| $y^*$ | | Reconciled values |
| $x$ | | System unknowns |

### Chapter 4

| | | |
|---|---|---|
| $\Delta$ | | Number of unrespected zero flowrate periods |
| $\mathbf{I}$ | | Index of periods |
| $k$ | | Number of profiles considered |
| $\omega$ | | Normalisation weight of profile |
| $p$ | | Profile of key driver of variation |
| $q$ | | Normalised value of profile |
| $r$ | | Reconstructed profile from $\mathbf{I}$ |
| $\sigma$ | | Standard deviation performance indicator |
| $\tau$ | | Cutoff value of profile |
| $T$ | | Total number of periods in profile p |
| $u$ | | Initial population of EMOO |
| $v$ | | Number of evaluated indexes in EMOO |
| $\mathbf{x}$ | | Precursor of vector $\mathbf{I}$ |
| $z_{i,t}$ | [1/0] | Counter of zero flowrate period in profile q |
| $\bar{z}_{i,t}$ | [1/0] | Counter of zero flowrate period in profile r |

### Chapter 5

| | | |
|---|---|---|
| $h_i$ | $[kj/kg]$ | Enthalpy of stream $i$ |
| $T_i$ | $[^\circ C]$ | Temperature of stream $i$ |
| $p_i$ | $[barg]$ | Pressure of stream $i$ |

### Chapter 6

**Sets**

| | |
|---|---|
| $b$ | Set of boilers |
| $G_{p,s}$ | Set of units of priority level $p$ in network $s$ |
| $h$ | Set of headers |
| $I_h$ | Set of units entering header $h$ |

| | | |
|---|---|---|
| $I_l$ | | Set of units entering letdown $l$ |
| $l$ | | Set of letdowns |
| $n$ | | Set of units |
| $O_h$ | | Set of units exiting header $h$ |
| $O_l$ | | Set of units exiting letdown $l$ |
| $q$ | | Set of process units |
| $s$ | | Set of individual networks |
| $T$ | | Set of time |

**Parameters**

| | | |
|---|---|---|
| $\alpha_l$ | $[-]$ | Desuperheating factor of letdown $l$ |
| $c_{n,t}$ | $[\$ \cdot h/t_{steam}]$ | Cost of unit $n$ at time $t$ |
| $d_t$ | $[h]$ | Duration of time period $t$ |
| $e_t$ | $[\$/Mwh]$ | Price of electricity at time $t$ |
| $F_{max,n,t}$ | $[t_{steam}/h]$ | Maximum flowrate of unit $n$ at time $t$ in tons per hour. |
| $F_{min,n,t}$ | $[t_{steam}/h]$ | Minimum flowrate of unit $n$ at time $t$ in tons per hour |
| $I_{fix,n}$ | $[\$/yr]$ | Fixed investment cost of unit $n$ |
| $I_{var,n}$ | $[\$/t_{steam} \cdot yr]$ | Variable investment cost of unit $n$ |
| $P_n$ | $[\$/h]$ | Shedding penalty cost of unit $n$ |
| $w_n$ | $[MW/t_{steam}]$ | Specific work of unit $n$ |
| $\lambda_b$ | $[1/h]$ | Mean failure rate of boiler $b$ |
| $\delta_b$ | $[d]$ | Maximum failure duration of boiler $b$ |

**Variables**

| | | |
|---|---|---|
| $c_{Op,n,t}$ | $[\$/h]$ | Operational costs of unit $n$ at time $t$ |
| $c_{Pen,n,t}$ | $[\$/h]$ | Penalty costs of unit $n$ at time $t$ |
| $c_{Inv,n}$ | $[\$]$ | Investment cost of unit $n$ |
| $\delta_{b,t}$ | $[h]$ | Duration of boiler failure of boiler $b$ |
| $F_n$ | $[t_{steam}]$ | Maximum unit $n$ flowrate |
| $F_{n,t}$ | $[t_{steam}/h]$ | Unit $n$ flowarte at time $t$ |
| $\bar{N}$ | $[\%]$ | Expected operability of steam network |
| $N_s$ | $[-]$ | Total shedding events in iteration of simulation |
| $N_y$ | $[-]$ | Total possible binary decisions concerning shedable units |
| $y_n$ | $[I/O]$ | Binary value for unit $n$ use over all time |
| $y_{n,t}$ | $[I/O]$ | Binary value for unit $n$ use at time $t$ |
| $x_{b,t}$ | $[-]$ | Decision variable for failure of boiler $b$ |
| $X_N$ | $[\%]$ | Operability interval (percentage of runs with operability above $N$ percent) |
| $w_{n,t}$ | $[MW]$ | Power of unit $n$ at time $t$ |

# 1 Introduction

*This chapter introduces the topic of energy in the refining and petrochemical industries. It presents available tools to improve energy efficiency and their gaps, followed by the objectives and an outline of this thesis.*

Energy is an enabler of work which has strongly contributed to growth and development of our societies. The industrial and electrified nature of developed societies depend on continued access to energetic resources. The same will be true for developing societies. Regardless of economic and environmental factors, fossil fuels are expected to play a significant role in the energy mix of future generations.

However, energy sourced from fossil fuels continues to contribute towards global warming. The COP-21 Paris Accords have set to reduce $CO_2$ emissions from 36 $Gt_{CO_2}$ in 2015 to 14 $Gt_{CO_2}$ in 2050 [1] so as to limit the temperature increase resulting from Global Warming to 2°C.

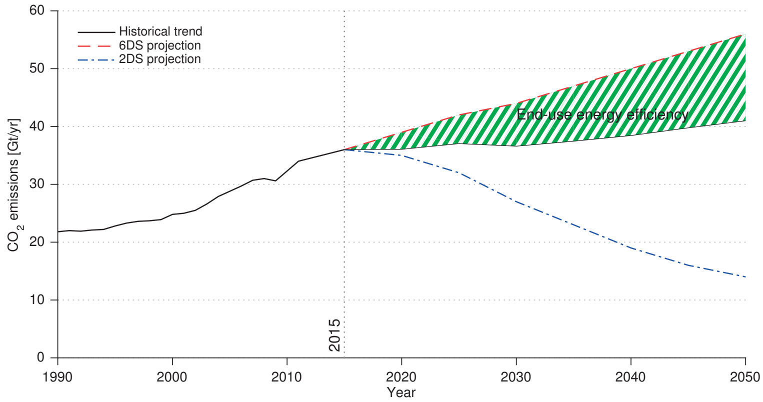



Figure 1.1 – Recorded $CO_2$ emissions to date and estimated trends according to the 6°C and 2°C scenarios [1].

Figure 1.1 shows the increase in $CO_2$ emissions between 1990 and 2015 and their expected trends according to the business as usual scenario (6°C) and the 2°C scenario. To meet the 2°C targets, end-use energy efficiency and better fuel use is expected to avoid emitting 15 $Gt_{CO_2}$ each year by 2050, the remainder coming from increased use of renewable energy sources, carbon capture and storage and fossil fuel switching.

The challenge of today's engineers is therefore to accommodate for increased end-use consumption of energy in the years to come, while reducing the $CO_2$ emissions released as a result. Energy also carries a high cost for industry, with direct purchasing costs and indirect $CO_2$ emissions taxes in Europe for example.

Industrial energy systems have been chosen as the focus of this thesis. For such systems, renewable energy sources may one day play a more important role, however, in the near future, conventional fossil fuels will continue to supply the brunt of the energy sources. Identifying energy efficiency solutions to simultaneously reduce energy costs and emissions creates an opportunity to increase competitiveness and contribute towards the emissions targets.

This chapter presents energy use in industry in Section 1.1 followed by a brief description of the refining and petrochemical industries in Section 1.2. The notion of energy efficiency in industry is presented in Section 1.3 as well as the tools to reach it. The aims and a synthesis of the thesis are described in Section 1.4.

Within the European context, one cannot talk about energy without mentioning the European Energy Efficiency Directive (EED) passed into law in 2012 [2] to reach the 2020 targets of reducing energy consumption by 20%. As a result of this law, large companies in Europe have the obligation to take part in regular energy audits to identify energy saving potential. These audits are likely to be the major drivers towards energy efficiency in Europe in the years to come, though they can be circumvented through the development of internal Energy Management Systems (EnMS) for example resulting from ISO50001 certification [3].

## 1.1 Energy in industry

Fossil fuels are the most commonly used energy vectors in industry. Energy vectors are defined as streams which may be used to transport or store energy [4]. Figure 1.2 shows the energy vectors consumed by industry in the USA in 2015 [5]. Coal, natural gas and petroleum products dominate the energy vectors of American industry in general, followed by electricity imported from the National Grid.

While electricity may be directly used by PUs, fossil fuel based energy resources are transformed into different vectors such as electricity, steam or thermal energy so as to supply a service. Many energy vectors have a dual nature, with the ability to be used as a feedstock for a conversion process or as a direct energy source. For example, natural gas may be reformed into hydrogen, or burned in a furnace to release heat.

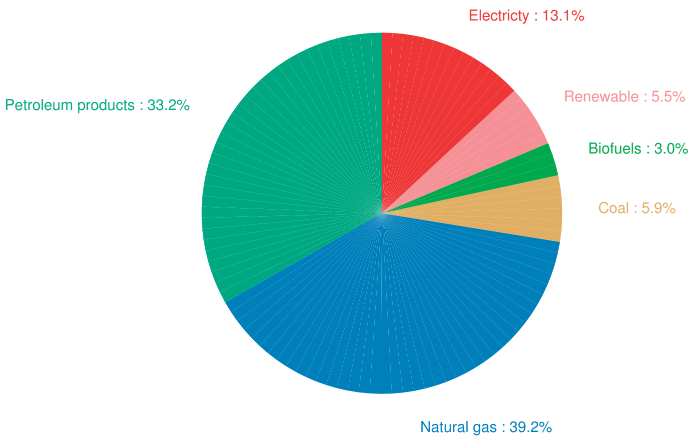



Figure 1.2 – Energy delivery according to vector in the USA industry in 2015 [5].

To understand industrial energy consumption it is necessary to understand industrial sites, an overview is shown in Figure 1.3 [6]. Dotted lines symbolise that multiple flows or units may exist. The figure shows the highly interlinked nature of industrial sites and their dependencies.

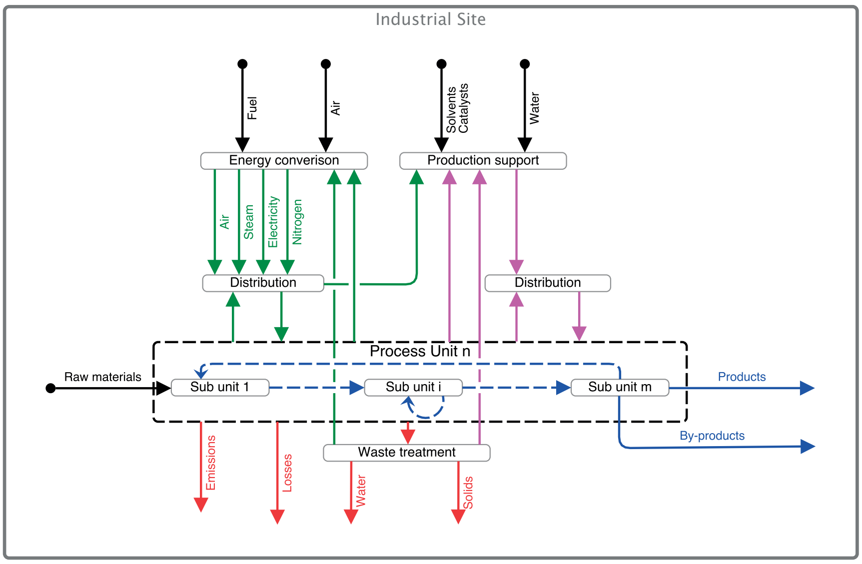



Figure 1.3 – Example of industrial site material and energy flows.

When several industrial sites share a geographical area, the ensemble can be referred to as an industrial cluster. Industrial sites are made up of Process Units (PUs) in dotted lines, which transform or manufacture goods. Horizontal lines refer to materials which are imported from outside the Industrial Site boundaries. Blue lines refer to intermediary and final products, some of which may be recycled. PUs are made up of a number of sub-units. These fulfil all the functions of conversion of input material to PU production.

Utility systems make up the energy, material and logistical support needed for PU operations to take place.

Production support streams can include the delivery of chemicals or other services contributing towards PU operations, for example the preparation and transfer of demineralised water for chemical processes or the preparation of compressed air to activate machinery.

Losses may take the form of material or energetic streams. Waste products may be solid or liquid. Some of these can be recovered and recycled for production support (clean water for example) or energy conversion (biogas for example).

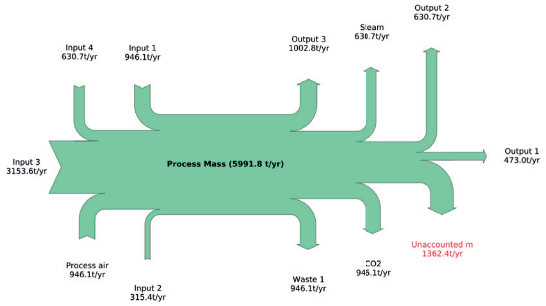
Streams entering the energy conversion box refer to energy vectors which may be consumed as thermal, chemical or electrical energy in PUs, or further transformed and stored.

Given the nature of energy, it is difficult to clearly differentiate between production support streams and energy vectors. When dealing with chemical processes, most material streams may simultaneously contribute towards the mass and energy balances of the reactions. They may also contribute distinctively to both. For example, hydrogen can be fixed to nitrogen to produce ammonia, or burned in a reactor to generate steam.

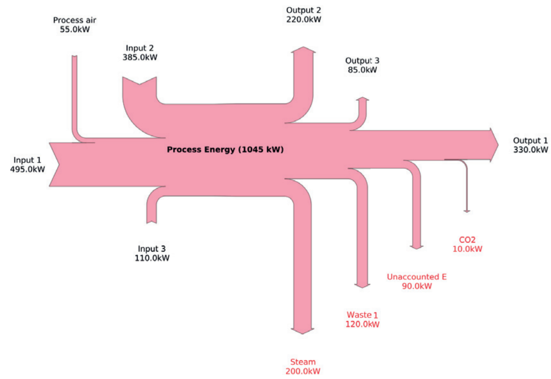
Quantifying all streams with respect to their mass and energy contents provides an elegant alternative to complicated labelling. An example is given in Figure 1.4 in which mass, energy and financial flows are represented. The same streams are represented in three different ways to quantify their contributions.

Understanding the inputs and outputs of a system according to their nature is a key step towards identifying energy efficiency solutions. For example, the unknowns of a system may hide valuable resources, just as a neglected mass stream can potentially be valued if it has a high energy content. The simplest way to understand the energy flows in industry is to start with financial flows, which account for most mass flows. However, some properties may be unknown, such as the unaccounted mass in (a) leading to unknowns in the energy flows in (b).

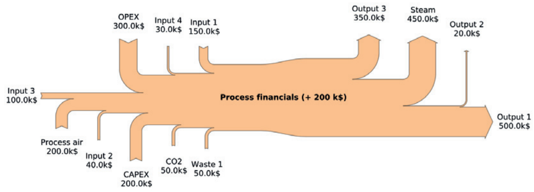
The focus of this thesis is energy in refineries and petrochemical sites as they are significant energy consumers. Reducing the energy requirements of these industries therefore has a direct impact on industry costs and emission outputs. As the fossil fuel burned to generate steam were estimated to be responsible for 31% of energy consumption by manufacturing in 2010 in the USA [7], steam is a major focus of this work. Complementary works should be sure to focus on electricity.




(a) Mass flows.




(b) Energy flows.




(c) Financial flows.

Figure 1.4 – Mass (a), Energy (b) and Financial (c) representations of Process Unit flows.

## 1.2 Energy in the refining and petrochemical industries

Refineries and petrochemical sites are often located close to each other in industrial clusters. The reasons for this proximity are that they often share products and require similar infrastructure. They may also make use of symbiosis between sites to reduce costs, for example through the installation of common utility systems. The refining and petrochemical sectors are briefly described below, as well as their energy uses.

### 1.2.1 Refineries

Refineries convert crude oil into refined petroleum products. These include asphalt, fuel oils, diesel, gasoline, kerosene and naphtha. Figure 1.5 shows the main PUs of a refinery, and their principal products. Intermediate products may be blended to meet market specificities and environmental constraints. Some of the key process units are briefly described below. Readers are referred to more detailed sources for more explanations [8]. Refineries typically lie on major transport routes to benefit from multiple sources of crude oil shipped by pipeline or by oil tankers as well as ready access to their markets.

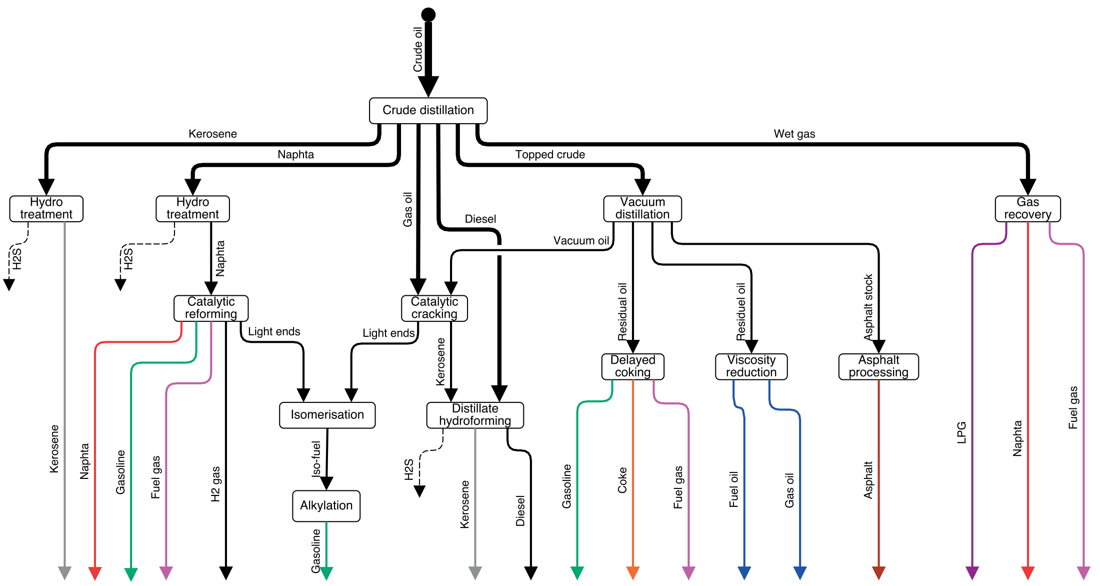



Figure 1.5 – Schematic of refinery mass flows.

- Crude distillation: This is the heart of a refinery, in which crude oil is boiled and distilled at atmospheric pressure. This PU supplies all other refinery PUs with feedstock. Significant energy consumption takes place in this PU as its throughput can be important. The crude oil is desalted, evaporated in a furnace (around 400°C) and separated into its major petrochemical fractions. Steam is typically injected into the column bottom to aid the evaporation.
- Vacuum distillation: The heavy petrochemical fractions are distilled in a vacuum. The heaviest products of this PU are the asphalts, which then go on to make our roads.
- Hydrotreatment: The principal function of this PU is to reduce the potentially corrosive sulphur compounds of the petrochemical fractions. Petrochemical fractions are reacted with hydrogen in the presence of a catalyst to produce hydrogen sulphide gas ($H_2S$) which can be separated and disposed of.
- Catalytic reforming: The octane rating of petroleum fractions are upgraded in this PU, in the presence of a catalyst. This PU also produces benzene, toluene and xylene which are important feedstocks for the petrochemical industry.
- Catalytic cracking: Long chain molecules are broken into smaller higher value molecules in the presence of a catalyst (whose temperatures may be very high).
- Distillate hydroforming: Petrochemical fractions are passed over a catalyst in the presence of hydrogen to increase their octane ratings.

The conversion efficiency of a refinery can be as high as 93%, meaning that 7% of the initial mass of crude oil is either used to provide energy to the PUs or evacuated as a waste products [9]. Waste streams are typically small as low value petrochemical fractions can be transformed into higher value products in PUs. It should be noted that each PU of a refinery consumes energy in varied forms, for example steam for heating and improved distillation, electricity to power machinery or fuel and natural gases to provide heat to processes.

To refine 1 kg of crude oil into its final products, 27.8 Wh of electricity, 180.4 Wh of steam and 610.5 Wh of combustible fuel are required [9]. It is estimated that $4.2 \times 10^{12}$ kg of oil were refined in 2014 [10], meaning that 3.4 PWh of end-use energy was consumed in refineries [1]. This amounts to 2.1% of overall worldwide energy consumption.

### 1.2.2 Petrochemical sites

Petrochemical sites convert olefins, aromatics and natural gas into higher value products, making up many of the base products for the plastics industry, many chemical industry feedstocks, synthetic fibres, ammonia and other materials. For an extensive list of petrochemical products, readers are referred to [11] as they number in the hundreds. As in the refining industry, petrochemistry has a high material conversion efficiency, with many side products being recycled or consumed within. Due to the petrochemical industries' reliance on refining products, these may be built next to each other and at minimum lie on major transport axes.

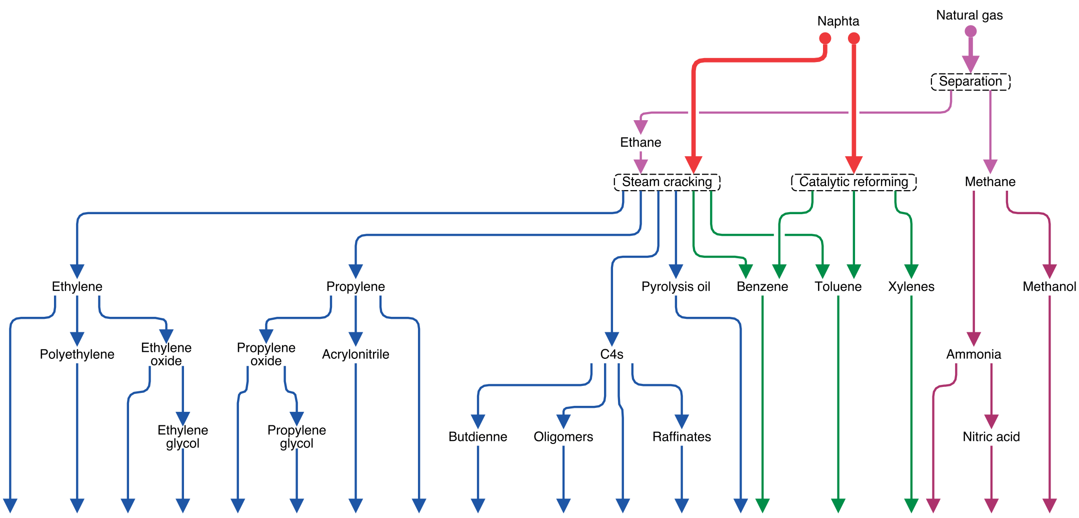



Figure 1.6 – Schematic of petrochemistry conversion pathways.

Figure 1.6 illustrates the conversion pathways of oil fractions and methane into some of their end products.

1. end-use energy consumption does not take into consideration the conversion losses of electricity or steam.

Olefins, are sourced from naphtha produced in refineries. They are converted into ethylene, propylene and butadiene (C4s) through steam cracking. Shale gas has also proven to be an economically interesting source of ethane to be converted into ethylene [12]. The importance of these base products for societal needs should not be underestimated.

Aromatics, are produced in catalytic reformers in refineries and petrochemical sites. Benzene, toluene and xylenes are the principal feedstocks of the aromatics industry which is required as a intermediary product for countless consumer goods.

Methane is used to produce ammonia and methanol, which supply the fertilizer, explosives and chemical industries with key feedstocks.

Each conversion of a feedstock into intermediary product implies significant energy input or output. For example steam cracking is endothermic and polymerisation of ethylene and propylene are exothermic. The industry consumes an estimated 3.5 MWh of energy per ton of high value chemical [13]. The combined petrochemical and chemical industries are estimated to consume 7% of worldwide energy [14].

## 1.3 Energy efficiency in industry

The International Energy Agency defines energy efficiency as *a way of managing and restraining the growth in energy consumption* [15]. A more technical definition might be the proportion of energy that is converted into useful work within a process, as shown in Equation 1.1. System losses can also be used to calculate efficiency.

$$\eta = \frac{E_{useful}}{E_{in}} = 1 - \frac{Losses}{E_{in}} \tag{1.1}$$

For this work, no rigorous definition of energy efficiency is introduced, rather it is proposed as a concept by which attempts are made to reduce the energy consumption of a system and the losses of its sub-systems. The aim of this dual approach when applied to industrial sites is to maintain production levels while reducing their overall energy consumption. As industry is driven by costs, energy efficiency solutions should contribute towards their decrease as well.

Four sectors can be addressed to identify energy efficiency solutions [16]:

1. Housekeeping: Ensure that processes are operating properly without impediments.
2. Control: Optimised operations through simple or advanced control techniques.
3. Modification: Replacement of inefficient technologies with efficient ones.
4. Integration: Maximise re-use of internal energy sources within processes.

The first two points relate to the day-to-day operations of industrial systems. Advanced control systems may be costly and high-tech requiring state-of-the-art methods. The last two points relate to modifications of system infrastructure, and should be carried out simultaneously. Little science is necessary for point 3 while point 4 may require state-of-the-art methods to identify optimised solutions.

Though control systems are very important to minimising energy consumption, integration is chosen as the focus of this thesis to identify investment solutions offering a maximum potential of energy recovery for industrial sites.

Energy Integration is an approach to system design and retrofit in which energy consumption of sub-units of systems are optimised as a whole rather than independently. In this way, the most is made of available energy sources within a system before considering importing energy. The quality of energy sources is the major consideration of Energy Integration, making sure to use high quality sources sparingly and avoid degrading them. For example, electricity can be used for process heating, though a low temperature waste heat source might be able to accomplish the same task at a lower economic cost with reduced energy import.

### 1.3.1 Pinch Analysis

Pinch Analysis [17] was developed as a tool to identify the maximum heat recovery potential of processes. It is the industry standrad tool for optimising heat transfer networks. It shows engineers how best to match process heat sources with cold sources and how to build the heat exchanger network to connect them. While other heuristic methods exist to design heat exchanger networks, Pinch Analysis is the only one to target maximum energy recovery.

This method is best applied within PUs of an industrial site as it suffers from limitations when applied to larger scales. Integration implies interconnecting sub-units with one another thereby making them interdependent. While this may be practicable within a PU, linking multiple PUs together in such a way would not be conducive to the flexible operations that they require. Furthermore, Pinch Analysis is limited to the heat exchanges of a PU, neglecting the very important electricity supplied to industrial sites. Other limitations appear as a result of the size and intricacies of industrial sites.

### 1.3.2 Total Site Analysis

Total Site Analysis [18] was developed to circumvent the limitations of the application of Pinch Analysis to industrial sites. It focuses on the utility networks of industrial sites rather than direct Process Integration between sub-units of multiple PUs. Through the elaboration of a shared utility network, for example a steam network, PUs may share their available heat sources in an optimal fashion.

This method assumes that heat recovery has already been achieved within PUs through Pinch Analysis. It is also able to address the electricity network of industrial sites.

The limitations of this method mainly include a lack of clear guidelines for its application to the petrochemical and refining industries, the significant amount of data that it requires and complicated generation of results as a consequence. Typical applications of this method fail to properly communicate the operability and hidden costs of the proposed solutions.

## 1.4 Thesis objectives and outline

*From data collection to engineering studies, this thesis presents a methodology to identify energy efficiency and energy integration solutions in the utility networks of refining and petrochemical sites.*

This thesis aims to identify energy efficiency solutions in the refining and petrochemical industries, through Energy Integration and other state-of-the-art methods. The end aim of such solutions is to reduce operational costs and emissions of sites with minimal investments, while taking care to ensure their operability and resilience.

Pinch Analysis and Total Site Analysis have already been extensively researched and applied, though both are still hindered by limitations. As this thesis focuses on industrial energy systems, Total Site Analysis is chosen as the pathway towards energy efficiency under the assumption that individual PUs are already optimised from a thermal point of view.

The chapters of this thesis are briefly described below. They follow the narrative of a typical engineering study. Necessary data is identified, methods to improve its quality and prepare it for Total Site Analyses are firstly proposed. A detailed adaptation of the Total Site Analysis methodology to the refining and petrochemical industries follows to identify energy efficiency solutions. Tools to optimise the operations of their utility networks and their energy efficiency solutions establish their operability and resilience.

### 1.4.1 Chapter 2: Typical Chemical Cluster

*Present the workings and particularities of a utility network in the refining and petrochemical industry as well as its typical data. The methods developed in this thesis are all applied to this data in their case studies.*

This chapter describes the typical architecture utility networks in such a refining and petrochemical cluster. The data concerning the demand for steam and cooling utilities is presented in detail as it forms the basis of the data used for the case studies in the following chapters.

An analysis of this time series data spanning 365 days reveals:

- The complexity of industrial steam network operations. Steam is produced and consumed at multiple pressure levels, with varying flowrates throughout the year.
- Incoherent data stemming from open mass balances. As a result of low measurement accuracy and unmeasured flows, steam production does not match the steam consumption meaning that energy balances cannot be closed.

The closing of energy balances is a pre-requisite for the application of Energy Integration and efficiency methods. Data quality must therefore be improved and missing steam must be calculated before any such methods can be tested.

New steam boiler investments are required for the Typical Chemical Cluster, each case study in the chapters to come build towards that aim.

### 1.4.2 Chapter 3: Data Reconciliation in the Refining and Petrochemical industries

*Propose a methodology to improve the quality of data in steam networks and calculate unmeasured properties so as to close mass and energy balances.*

Data Reconciliation is a methodology which serves to improve data quality of measurements. It can be used to identify erroneous measurements of metering systems, propose coherent values for them as well as calculate unknown properties of a system.

In this chapter, a step-by-step methodology is developed to model and reconcile steam networks, including which data to collect and how to filter it. Special attention is paid to previously unquantified flows such as letdown, turbine and losses flowrates.

The proposed methodology is applied to the steam network data of the Typical Chemical Cluster thereby closing the mass balances. The results reveal that steam demand is underestimated as a result of unknown consumers and losses.

### 1.4.3 Chapter 4: Identification of representative periods

*Propose a methodology to identify representative operational scenarios of multiple process units.*

Defining the appropriate data to use for an engineering study is complicated as modern industrial data measurement systems have very high resolutions of data. This is not always helpful to engineers in their work, nor in their communication of findings to decision-makers.

Scenario based approaches are common practise for engineering studies, identifying representative operations of industrial sites, allowing for accurate results to be produced. Often based on process knowledge, when considering a large industrial site or cluster, obtaining such knowledge is challenging.

This chapter therefore proposes a computer aided methodology for the identification of representative operating periods common to multiple process units within a cluster or site. From these periods, realistic scenarios can be obtained which respect the variations and key properties of the data.

The methodology is applied to the reconciled data from the case study to identify a manageable number of scenarios which can be used to carry out a multi-period Total Site Analysis.

### 1.4.4 Chapter 5: Multi-period Total Site Analysis

*Propose a step-by-step methodology to perform Total Site Analyses in the refining and petrochemical industries.*

Total Site Analysis is a mature technology for the identification of energy integration solutions in industrial sites and clusters. Through it, optimal utility network designs or modifications can be identified, leading to potentially increased energy efficiency.

A review of literature on the subject reveals that little information is available on which data to collect and how to model it efficiently. This chapter therefore proposes a step-by-step methodology for minimal data collection, process stream modelling and results generation. It is specifically tuned towards the refining and petrochemical industry. The most common types of energy transfers with steam and cooling networks are defined. Using the proposed methodology, complex systems can be considered in a simpler form.

A multi-period Total Site Analysis is carried out on the case study, using periods identified in Chapter 4. The results show that the multi-period approach is necessary as key thermodynamic properties of the systems vary significantly with time. An energy efficiency solution with the potential to appreciably reduce overall energy demand is also proposed.

### 1.4.5 Chapter 6: Optimal operations and resilient investments in steam networks

*Propose a methodology to optimise operations and evaluate the resilience and operability of proposed investments and energy efficiency solutions.*

Operations of utility systems can be very costly for large industrial sites, as can their investments. For these reasons, mathematical formulations were created to optimise operations of utility networks and identify minimal investment opportunities. While optimal operations can be targeted by operators, the minimised investments are unrealistic as they would lead to bare minimum installed capacities and would not be able to deal with fluctuating demand.

This chapter therefore focuses on the operability of steam networks. By including load shedding into existing mathematical formulations, it is possible to minimise and quantify the impacts of low generation capacity on networks. By simulating boiler failures, the resilience of the steam network is then established.

Using these formulations, the day-to-day operations of existing networks and their investment options can be analysed, as can their resilience to perturbatory events such as boiler failures. Integrating Total Site Analysis solutions into to optimisation of steam networks allows for more clear communication of findings due to an improved understanding of their impacts and operability.

The proposed methods are firstly applied to the case study to establish the optimal operations of its steam network. The method is also used to evaluate the feasibility of the energy integration solution established in Chapter 5. Several investments are then defined and tested to simultaneously increase energy efficiency and provide resilient operations for the Typical Chemical Cluster.

# 2 Typical Chemical Cluster

*This chapter presents the steam and cooling demand of a typical refining and petrochemical cluster, so as to inform readers about the particularities of the industry. The data presented below is used in all the cases studies of this thesis.*

## 2.1 Introduction

The aim of this thesis is to investigate energy efficiency and integration measures in the refining and petrochemical industries, with a particular focus on the steam networks. It is therefore necessary determine the contributors to steam supply and demand as well as their properties. A case study is proposed in order to establish these properties for a typical industrial site. In an effort to increase readability, all the developed methods of this thesis are applied the this case study.

The case study concerns an industrial cluster made up of a refinery and a petrochemical site, referred to as the Typical Chemical Cluster (TIC). Refineries are often coupled to petrochemical sites as many of the refining products and derivatives are further transformed in the adjoined petrochemical sites. Other synergies, for example in the utility networks are also made possible through the geographical proximity of the sites.

Given the confidential nature of the industry, the topology of the sites and the data used for the case study is presented below in an anonymised form. Process Unit (PU) names and descriptions are omitted or only briefly described and all data has been scaled by a constant factor in order to be unrecognisable while maintaining its realistic nature.

### 2.1.1 Choice in data

Data collection and treatment is the most time consuming part of any energy efficiency study. The aim of data collection should be to obtain enough information to close the mass and energy balances and identify representative operational modes of the equipments. Process knowledge and experience in the field are the factors which allow for efficient data collection.

Data can be acquired in the following forms, with specific considerations.

- Online measured data: This time series data corresponds to measured or calculated values that communicate the variation of a property through time. Servers typically store data as discrete data points. The data can be acquired for pre-defined time steps, either as:

  - Time averaged: An average value is taken between time $t$ and $t+1$.

  - Time sampled: A spot value is taken from time $t$.

  The resolution of time-series data should be adapted to each type of study.

- Spot measured data: Data obtained through manual sampling. One must always consider the operating conditions at time of sampling to determine accuracy and representativeness of the data.

- Design data: Data corresponding to the original design plans of a plant or process. Care must be taken as PUs often operate outside of their design conditions. Process retrofits, which may not always be clearly detailed can lead to additional variations in these values.

- Estimates: Data obtained through calculation and process knowledge. While estimates should be avoided when possible, they are often necessary given the scale of industrial sites. Engineers must make efforts to identify the sources of the estimates and justify their chosen values.

Data should be verifiable and provide the means to calculate efficiency solutions which match the operating conditions of the individual sites. For example, yearly mean values do not provide any information on the minimum, nominal and maximum values and therefore should not be used without special considerations. Using very high resolution data can often lead to complex engineering calculations. A compromise should therefore be made between the resolution of data and its relevance, the aim being to work with representative data.

The online data used for the case study presented in this thesis was taken from the 1st of January 2014 to the 31st of December 2014. The year in question was considered to be representative of typical operations given the relatively high output of the PUs during that time as well as a system failure leading to several PU D in Site R and then several other PUs going offline. These sorts of incidents may be infrequent but they are important aspects of a cluster's operations. Averaged daily data was sampled from data servers.

### 2.1.2 Typical Chemical Cluster narrative

The proposed TIC is made up of a Refinery (Site R), a Petrochemical site (Site P) and a Central Boilerhouse (CB) which supplies steam to both sites. A map of the TIC is shown in Figure 2.1 with Site R on the left and Site P on the right. Site R is larger than Site P given the important number of storage tanks for crude oil and its refining products. The TIC is located on a large river and has access to shipping, road and rail infrastructures.

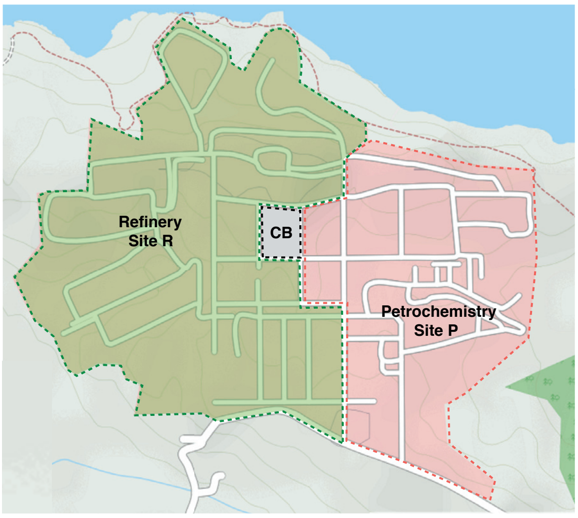



Figure 2.1 – Map of the typical cluster.

The individual sites operate independently from one another and both have boilerhouses to supply their steam demand. The Central Boilerhouse is owned by a third party, which sells steam to the Site R and P for profit.

Sites R and P were constructed at the same time by a single company. Site R refines crude oil and exports naphtha (a key feedstock of Site P), fuels for auto-mobiles, aircrafts and ships as well as bituminous products. The sites and their networks were mostly built independently of each other so as to limit the effects of cascading events. Today Site R and P have separate ownership.

The steam networks are very similar in configuration and operations, with similar architectures of boilers and utility systems. The boilers of Sites R and P were recently upgraded to burn natural gas, however the CB boilers never underwent this retrofit and therefore still burn oil.

The CB provides steam to Sites R and P when demand is high, or when some of their own boilers are offline. The boilers of the CB are old and will require important investments in the near future to remain operational. The third party owning the CB boilers has indicated that the boilers will be decommissioned without re-investment.

Given the economic conjecture, for the past few years both industrial sites have reduced their maintenance budgets have leading to the apparition of many leaks in the steam network and an increase in the number of defective steam traps [44].

When the sites were constructed, energy costs were low. Steam and electricity were often considered to be a cheap utility to which little attention was paid. Over time this mentality has changed and energy costs have now become an important aspect of operational cost reductions second only to process efficiency.

With the introduction of strict environmental controls on air quality, Sites R and P have replaced the oil burners of their boilers by gas burners to reduce the $NO_x$ emissions and eliminate $SO_x$ emissions altogether. Replacing oil with natural gas has led to a reduction of $CO_2$ emissions which the TIC must pay taxes on.

Both sites are interested in further reducing costs, leading to a number of optimisation studies to identify least cost investment and operations solutions. The management of both sites has expressed a desire to work together, for example on symbiosis projects to reduce operational costs [1]. Operators across both sites welcome change, at the condition that operations are not affected. Therefore, identified solutions can only be implemented if they can be shown not to impact the operability of either site.

### 2.1.3 Typical Chemical Cluster description

The steam network architecture of the TIC is presented in Section 2.2 and the steam demand in Section 2.3. The two industrial sites making up the TIC are both made up of 6 PU complexes (named A to F) and extensive utility systems. These PUs are briefly detailed in Tables 2.5 and 2.7.

Process cooling takes place through the generation of steam, aero cooling and water cooling, described in Section 2.4. The operational constraints (load shedding plans) are also described in Section 2.5, indicating the order in which to shutdown the PUs in case of emergency.

The electric network of the TIC is not described as it can be considered to operate autonomously from the steam network and has not been the subject of detailed optimisation studies in this thesis.

Energy efficiency within PUs of the refining and petrochemical industry are not addressed either in this work, as the focus has been on utility systems and their optimisation.

## 2.2 Steam network architecture

Figure 2.2 shows the layout of the TIC's steam network and its interconnections. High pressure superheated steam is created in the boilers of Site R (RB1, RB2), Site P (PB1, PB2, PB3) and the Central Boilerhouse (CB1, CB2) and sent into the high pressure headers of the sites. No connections exist between the networks of Site R and P, though both are supplied by the Central Boilerhouse in high pressure steam.

1. Engaging management is often cited as an key factor in successfully carrying out energy efficiency projects [23]

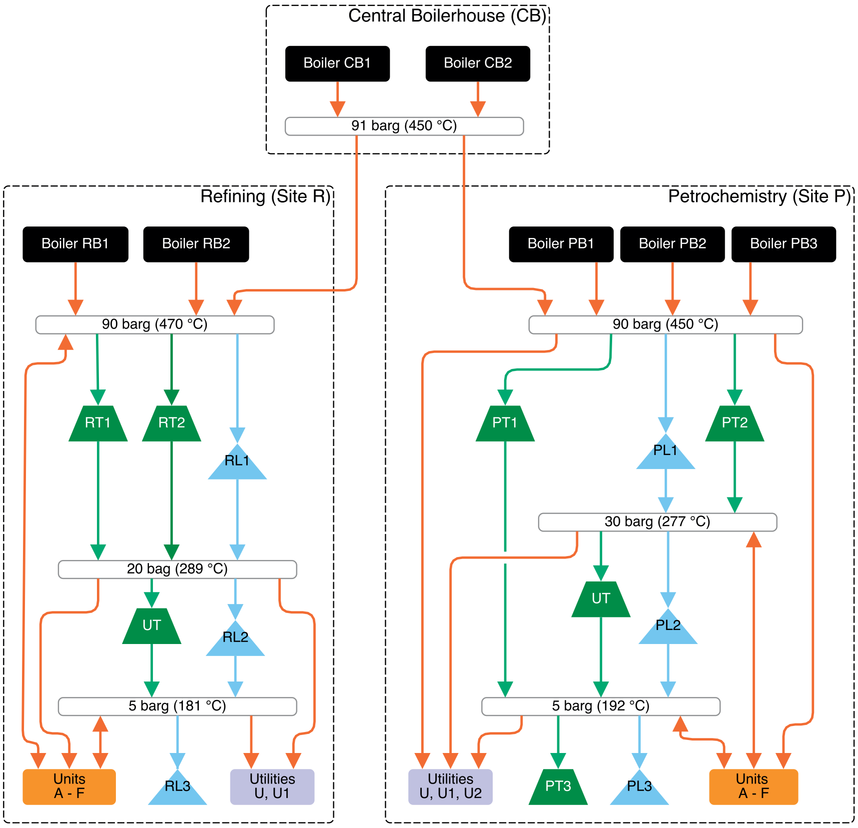



Figure 2.2 – Simplified schematic of the Typical Chemical Cluster steam network.

Both steam networks operates at three pressure levels.

- Site R: 90, 20 and 5 barg.
- Site P: 90, 30 and 5 barg.

### 2.2.1 Turbines

Cogeneration turbines (RT1, RT2, PT1, PT2, PT3) transport steam across pressure levels while producing electicity. In reality, the electricity produced in these turbines provides the electric safety net for the industrial sites though this is not taken into consideration in this work. Turbine PT3 is a condensing turbine, releasing excess 5 barg steam to the atmosphere. The properties of the cogeneration turbines are described in Table 2.1.

The Utility Turbines (UT) are made up of a number of turbines, which provide power for pumps to move fluids across the site, namely the site products and demineralised water. They are considered as a process requirement of the industrial sites. Throughout this work, these are also referred to as cogeneration turbines.

Table 2.1 – Turbine properties of the Typical Industrial Cluster.

| | Inlet [barg] | Outlet [barg] | Min [t/h] | Max [t/h] | Isentropic efficiency $\eta$ [%] |
|---|---|---|---|---|---|
| RT1 | 90 | 20 | 52 | 90 | 76 |
| RT2 | 90 | 20 | 52 | 90 | 75 |
| UT | 20 | 5 | 0 | 60 | 30 |
| PT1 | 90 | 5 | 12.6 | 62 | 62 |
| PT2 | 90 | 30 | 52 | 112 | 71 |
| PT3 | 5 | 0 | 12.5 | 38.5 | 60 |
| UT | 30 | 5 | 0 | 60 | 30 |

### 2.2.2 Letdowns

Isenthalpic letdowns (RL1, RL2, RL3, PL1, PL2, PL3) transport steam across the different steam headers. As the steam is superheated, these letdowns are coupled to desuperheaters. Desuperheaters inject demineralised water into the steam to simultaneously cool it down and increase steam production. Letdowns RL3 and PL3 release excess steam to the atmosphere. The properties of the letdowns are described in Table 2.2.

Table 2.2 – Letdown properties of the Typical Chemical Cluster.

| | Inlet [barg] | Outlet [barg] | Min [t/h] | Max [t/h] | Desuperheating temperature [° C] |
|---|---|---|---|---|---|
| RL1 | 90 | 20 | 0 | 220 | 250 |
| RL2 | 20 | 5 | 0 | 220 | 160 |
| RL3 | 5 | 0 | 0 | 100 | |
| PL1 | 90 | 30 | 0 | 400 | 260 |
| PL2 | 30 | 5 | 0 | 400 | 165 |
| PL3 | 5 | 0 | 0 | 100 | |

### 2.2.3 Water network and boilers

The water network can be represented schematically using Figure 2.3. The water network imports, demineralises and degases raw water (blue). The boilers and steam networks produce and transport the steam (red) across pressure levels to consumers through letdowns and turbines. PUs may also produce steam from demineralised water. Steam traps ensure that high steam quality is maintained. Condensates are either recovered (green) or discarded (grey) to a WasteWater Treatment Plant (WWTP) depending on their quality and the type of steam use.

The boilers and water networks are described below. Steam purges and losses are addressed in Section 2.6. The WWTP is not addressed in this work though they may offer potential for energy optimisation [30].

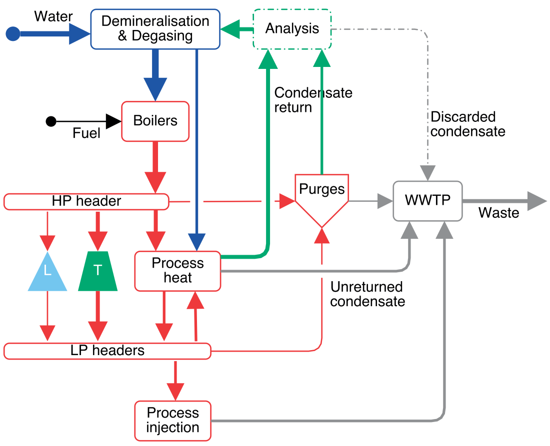



Figure 2.3 – Schematic of the water and steam network.

A schematic of the boiler configurations is presented in Figure 2.4 with average temperatures indicated. The properties of the boilers are described in Table 2.3. The price of steam production is expressed uniquely in $\$/t_{steam}$, which includes maintenance and fuel costs.

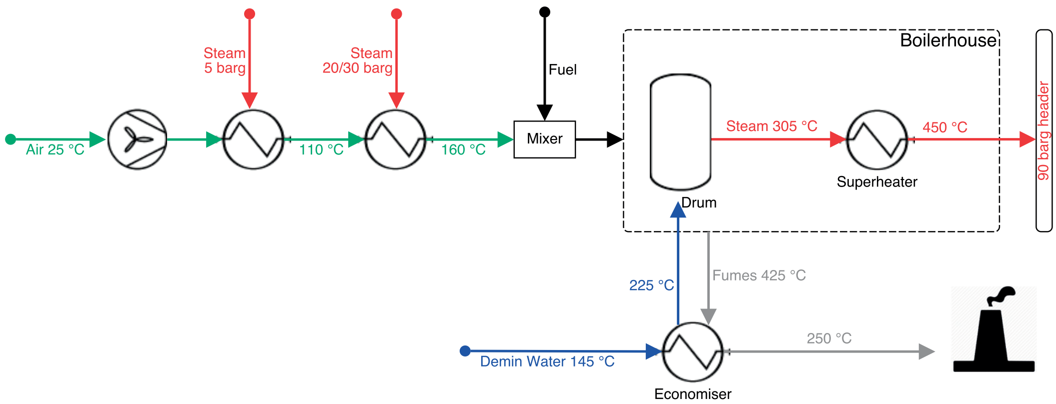



Figure 2.4 – Simplified boiler schematic.

Air (in green) is firstly preheated using 5 barg steam, bringing it to 110 °C and then with 20 barg steam in Site R and 30 barg steam in Site P, up to 160 °C . The fuel (in black) is burned and evaporates the pre-heated demineralised water in a drum and superheater producing 90 barg steam. Radiation dominates at high temperatures (1100 °C) while convection does in lower temperatures (between 1100 and 425 °C). The fumes (in grey) exiting the boiler are cooled in an economiser before being released to the atmosphere at approximately 250 °C .

Table 2.3 – Boiler properties of the Typical Industrial Cluster.

| | Outlet [barg] | Temperature [° C] | Min [t/h] | Max [t/h] | Failure rate $\lambda$ [-] | Steam price [$/$t$] | Fuel type |
|---|---|---|---|---|---|---|---|
| RB1 | 90 | 470 | 30 | 90 | 1/365 | 18 | Gas |
| RB2 | 90 | 450 | 30 | 90 | 1/365 | 18 | Gas |
| PB1 | 90 | 450 | 50 | 130 | 1.5/365 | 18 | Gas |
| PB2 | 90 | 450 | 50 | 130 | 1.5/365 | 18 | Gas |
| PB3 | 90 | 450 | 50 | 130 | 1.5/365 | 18 | Gas |
| CB1 | 91 | 450 | 30 | 130 | 2/365 | 25 | Oil |
| CB2 | 91 | 450 | 30 | 130 | 2/365 | 25 | Oil |
| Demin. water | | 145 | 0 | $\infty$ | | 5 | |

Pressurised demineralised water (in blue) arrives from the demineralisation plant at 145 °C and enters the economiser, bringing its temperature to 225 °C. The water evaporates at 305 °C and the superheater brings the steam (in red) to 450 °C in Site P and 470 °C in Site R. The steam is then released into the 90 barg headers.

The failure rate $\lambda$ in Table 2.3 refers to the frequency of boiler failures per year, otherwise known as the constant failure rate.

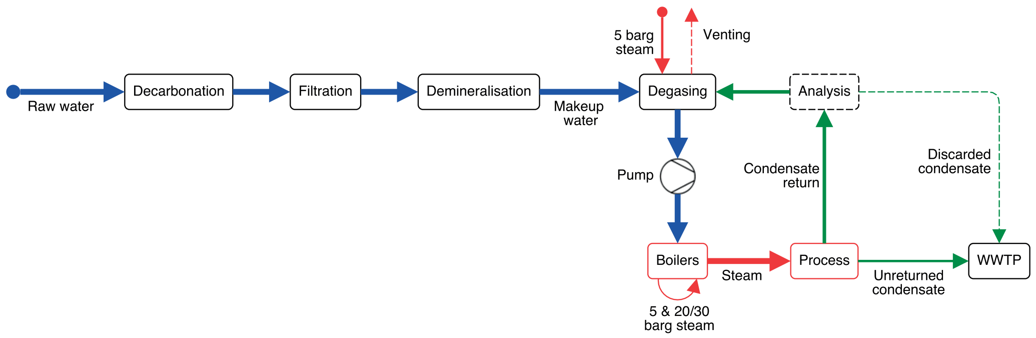



Figure 2.5 – Water network schematic.

The water treatment network is made up of the following processes, schematised in Figure 2.5.

- Decarbonation: Addition of chemicals to water to precipitate calcium.
- Filtration: Sand filtration removes organic and mineral particles from decarbonated water.
- Demineralisation: Anion and cation ion exchange to reduce the quantity of dissolved solids in the water.
- Degasing: 5 barg steam is injected into the demineralised water to strip it of its $O_2$ and $CO_2$ content, respectively reducing corrosion in the boilers and increasing the pH of the water to make it less aggressive.

Condensate returns undergo real-time analysis and are disposed of in the WWTP if pollutants are present. Clean condensates are flashed and mixed with the demineralised water before degasing. As Sites R and P cover large geographical areas, piping for condensate return is not installed on each steam trap or heat exchanger. Unreturned condensates are sent to a WWTP.

Table 2.4 – Mean measured water, steam and air flows for utilities in [t/h].

| | Output | Condensate return | | Makeup water | Air preheat | | Degas steam |
|---|---|---|---|---|---|---|---|
| | | 5 barg | 20/30 barg | | 5 barg | 20/30 barg | |
| Site R | 139.4 | 7.6 | 23.8 | 116.6 | 6.4 | 7.6 | 11.1 |
| Site P | 291.5 | 39.4 | 54.0 | 205.0 | 9.5 | 9.6 | 17.3 |
| CB | 8.7 | | | | | | |

Further details concerning the makeup water, condensate return and air preheating can be found in Table 2.4. It should be noted that the sum of the makeup water and condensate returns do not match the boiler output as data is not reconciled. As the Central Boilerhouse is operated by a third party and owns its own demineralisation plant, only its steam output to each site is obtained.

## 2.3 Steam demand

The most important property to consider in a steam network is the demand at each pressure level, that is to say the difference between the consumption and auto-production of steam (as a result of process cooling). The demand corresponds to the amount of steam that must be produced by the utility network to supply PUs and utility demand with steam.

The utility and production supports networks consume steam to operate properly. The are both referred to as utility steam demand and may include: boiler preheating, demineralised water degassing, tank tracing and steam turbine activation amongst others. Their share of overall steam demand can be significant on large sites.

The demands for the individual sites are presented in sections 2.3.1 and 2.3.2. Key properties of the steam demand include the mean and maximum steam demand. These properties are important for optimisation studies to calculate expected costs and avoid under or over-sizing the demand. The overall demand of the TIC is presented in Section 2.3.3. Considering the overall demand will permit global optimisation and symbiosis solutions to be proposed for the TIC.

Due to the important price of metering devices, not all steam consumptions and productions are measured. For this reason, the values presented in Sections 2.3.2 to 2.3.3 correspond to a combination of measured, calculated, estimated and design data.

The steam networks' thermal losses and physical losses (leaks and condensation) contribute towards the steam demand of an industrial site, though they are not quantified here. Losses are addressed in more detail in Section 2.6. This data corresponds to raw data, containing unknown flows and measurement errors. As such mass balances cannot be expected to close.

The cogeneration turbines (RT1, RT2, PT1, PT2) are not included in this analysis as they are not a process requirement. On the other hand, the utility turbines (UT) are included as they are necessary for the proper functioning of the site.

The analysis below presents the steam demand for the PUs of Sites R and P. The internal consumption of steam for the PUs is detailed in Appendix A.

### 2.3.1 Site R

Site R is made up of six PU complexes, consuming and producing steam at various pressure levels. The principal function of each PU is briefly described in table 2.5 along with the types of steam usage. High pressure 90 barg steam is produced in the furnaces of PU D, while 90 barg is only consumed in PU C, used to power a turbo-compressor. Several such cogenerating devices (turbo-pumps) exist throughout Site R, consuming 20 barg steam and release it at 5 barg.

Table 2.5 – Key function of units and steam consumption type for Site R.

| | Function | Production | Consumption | Cogeneration | Injection | Tracing | Losses |
|---|---|---|---|---|---|---|---|
| Unit A | Separation | x | x | x | x | x | x |
| Unit B | Isomerisation | x | x | | x | x | x |
| Unit C | Hydrogenation | x | x | x | x | x | x |
| Unit D | Cracker | x | x | x | x | x | x |
| Unit E | Separation | | x | | | | x |
| Unit F | Purification | x | x | | | | x |
| Utilities (U) | Boiler, Degaz | | x | | | x | |
| Utilities (U1) | Tracing | | | | | x | |
| Utilities (UT) | Turbo pumps | | | x | | | |

Table 2.6 shows the mean and maximum steam consumption for Site R over a representative year. Negative values indicate a net export of steam from the PU. In general this takes place as a result of the use of turbo-pumps.

PU D has the particularity of exploiting a 2 barg steam network which is not mentioned in Table 2.6 as the demand manifests itself in the form of 5 barg steam.

Figure 2.6 shows the 90 barg steam overview, with the production in graph (a) and the consumption in (b). The legend indicates the mean and maximum (mean/max) steam flowrates. 90 barg steam consumption is slightly higher than the production, with a mean consumption of 0.9 t/h and

Table 2.6 – Measured steam demand for Site R.
Mean demand: 155.1 t/h.

| | 90 barg [t/h] | | 20 barg [t/h] | | 5 barg [t/h] | |
|---|---|---|---|---|---|---|
| | Mean | Max | Mean | Max | Mean | Max |
| Unit A | | | 10.9 | 19.8 | -4.1 | -10.4 |
| Unit B | | | 10.3 | 16.5 | | |
| Unit C | 13.5 | 23.3 | 9.0 | 19.3 | -12.8 | -27.3 |
| Unit D | -12.6 | -20.0 | 7.5 | 18.5 | 8.2 | 18.6 |
| Unit E | | | 20.0 | 28.5 | 13.5 | 19.0 |
| Unit F | | | 16.0 | 28.0 | | |
| Utilities (U) | | | 31.8 | 67.2 | 26.2 | 33.1 |
| Utilities (U1) | | | 6.2 | 22.6 | 11.6 | 26.6 |
| Utilities (UT) | | | 26.9 | 48.1 | -26.9 | -48.1 |
| Atmosphere | | | | | 0.1 | 19.9 |
| Total | 0.9 | 21.1 | 138.4 | 180.2 | 15.8 | 43.6 |
| Boiler 1 | 70.4 | 90.8 | | | | |
| Boiler 2 | 79.3 | 90.8 | | | | |
| CB | 5.8 | 53.4 | | | | |


Figure 2.6 – Measured 90 barg steam production (a) and consumption (b) in Site R.

maximum of 21.1 t/h. The high value of the peak demand compared to the mean demand is caused by unsynchronised shutdown periods in PUs C and D. Following an accident on day 129, PU C goes offline for almost 100 days. On the day of the accident, several other PUs of Site R go offline as a result of cascading effects.

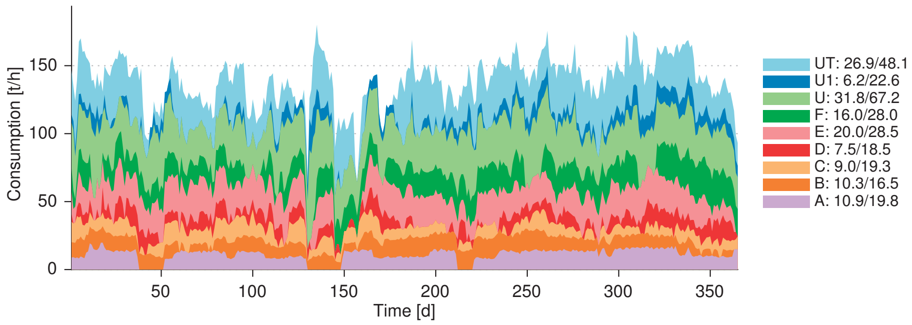



Figure 2.7 – Measured 20 barg steam consumption in Site R.

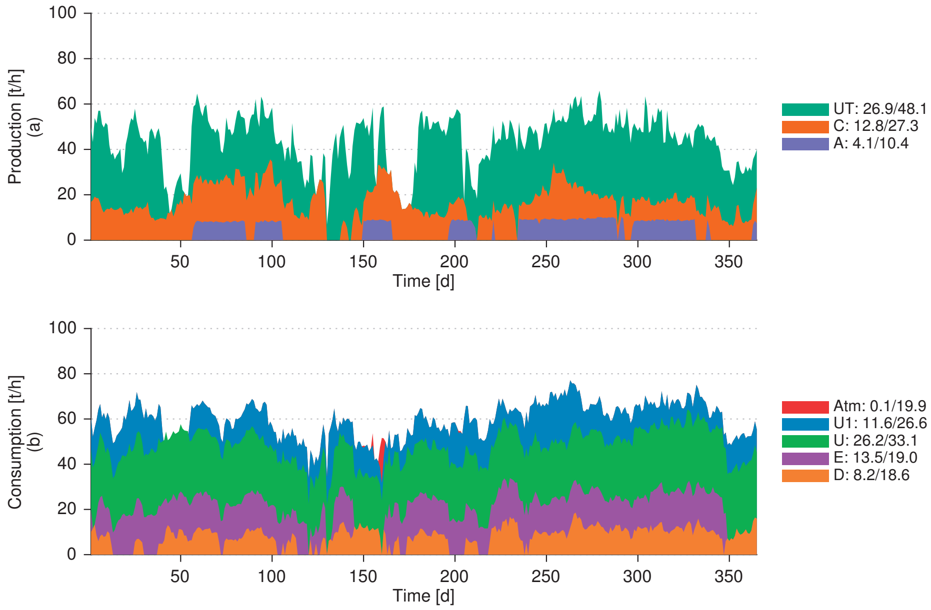



Figure 2.8 – Measured 5 barg steam production (a) and consumption (b) in Site R.

Figure 2.7 shows the consumption of 20 barg steam. No 20 barg steam is exported to the network by the PUs. The mean and maximum 20 barg demand are respectively 138.4 and 180.2 t/h. The principal consumer of 20 barg steam are the Utilities (U), reaching a peak value of 67.2 t/h.

The 5 barg steam production and consumption is shown in Figure 2.8, the mean demand is 15.8 t/h with a peak of 43.6 t/h. The production principally stems from PU C and the utility turbo-pumps (UT), letdown from 20 barg. PU A shows steps consistent with turbo-pump activation. Atmospheric venting only takes place for a short period of time, with a peak venting of 19.9 t/h.

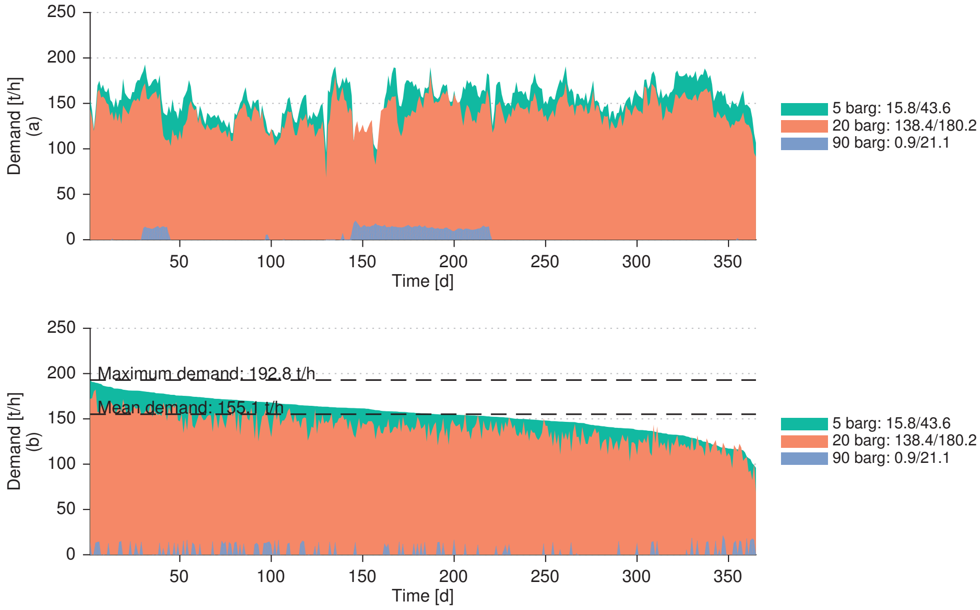



Figure 2.9 – Measured steam demand overview for Site R.

The overall steam demand for Site R is displayed in Figure 2.9 (a), with a mean demand of 155.1 t/h and maximum of 192.8 t/h. Graph (b) shows the load duration curve for Site R, in which the importance of the 20 barg consumption can be clearly seen. The curves also show that overall steam demand is not strongly related to on 90 barg steam demand.

The installed capacity of Site R is 180 t/h (2 × 90 t/h), meaning that if both boilers are online, there is always sufficient steam to supply demand. However, if one of them is offline, Site R is dependant on the Central Boilerhouse to supply almost half of its steam.

### 2.3.2 Site P

Six PUs are considered in Site P, briefly described in Table 2.7. Table 2.8 shows the mean steam consumption for Site P over a representative year. Negative values indicate a net export of steam from the PU. In general this takes place a a result of the use of turbo-compressors. PU B operates a 2 barg steam network, letdown from 5 barg.

The only demand for 90 barg steam takes place in PU A , shown in Figure 2.10. PU A is a cracker and also produces an equally important of 90 barg steam as a results of reactor cooling. The mean and peak demand for 90 barg steam are respectively 116.5 and 274.8 t/h which takes place when its furnaces are turned off.

Table 2.7 – Key function of units and steam consumption type for Site P.

| | Function | Production | Consumption | Cogeneration | Injection | Tracing | Losses |
|---|---|---|---|---|---|---|---|
| Unit A | Cracker | x | x | x | | | |
| Unit B | Butadien | | x | | | | |
| Unit C | Aromatics | | x | | | | |
| Unit D | Polymerisation | | x | | | | |
| Unit E | Oxidation | x | x | x | x | | |
| Unit F | Polymerisation | | x | | x | | |
| Utilities (U) | Boiler, Degaz | | x | | | x | |
| Utilities (U1) | Tracing | | | | | x | |
| Utilities (U2) | Tracing | | | | | x | |
| Utilities (UT) | Turbo pumps | | | x | | | |

Table 2.8 – Measured steam demand for Site P.
Mean demand: 325.1 t/h

| | 90 barg [t/h] | | 30 barg [t/h] | | 5 barg [t/h] | |
|---|---|---|---|---|---|---|
| | Mean | Max | Mean | Max | Mean | Max |
| Unit A | 116.5 | 274.8 | -55.7 | -134.9 | -38.7 | -148.9 |
| Unit B | | | 32.5 | 69.9 | 9.4 | 18.0 |
| Unit C | | | 62.0 | 93.7 | 12.9 | 21.7 |
| Unit D | | | 7.9 | 13.2 | | |
| Unit E | | | 46.2 | 69.6 | -29.3 | -52.4 |
| Unit F | | | 18.1 | 24.8 | 27.5 | 35.3 |
| Utilities (U) | | | 22.3 | 65.3 | 58.6 | 95.7 |
| Utilities (U1) | | | 0.9 | 8.9 | 14.4 | 21.7 |
| Utilities (U2) | | | 3.6 | 14.2 | 13.7 | 22.0 |
| Utilities (UT) | | | 4.7 | 5.5 | -4.7 | -5.5 |
| Atmosphere | | | | | 1.5 | 71.8 |
| Cond. turbine | | | | | 0.8 | 29.0 |
| Total | 116.5 | 274.8 | 142.6 | 244.6 | 66.0 | 148.1 |
| Boiler 1 | 122.5 | 129.2 | | | | |
| Boiler 2 | 124.9 | 130.8 | | | | |
| Boiler 3 | 52.9 | 124.2 | | | | |
| CB | 12.2 | 98.9 | | | | |

Figure 2.11 shows the 30 barg steam production (a) and consumption (b) over the chosen year. Though PU A consumes 30 barg steam internally, given the large amount of 90 barg steam used to power turbo-compressors, it has a net export of 30 barg steam. PU C is the principal consumer of 30 barg steam with a peak demand of 93.7 t/h. The mean overall demand for 30 barg steam is 142.6 t/h with a peak at 244.6 t/h.

Figure 2.12 shows the 5 barg steam production (a) and consumption (b) over the representative year. Most of the 5 barg steam production comes from PU A, also due to its intense use of turbines. PU E produces an important amount of 5 barg steam as well due to the exothermic

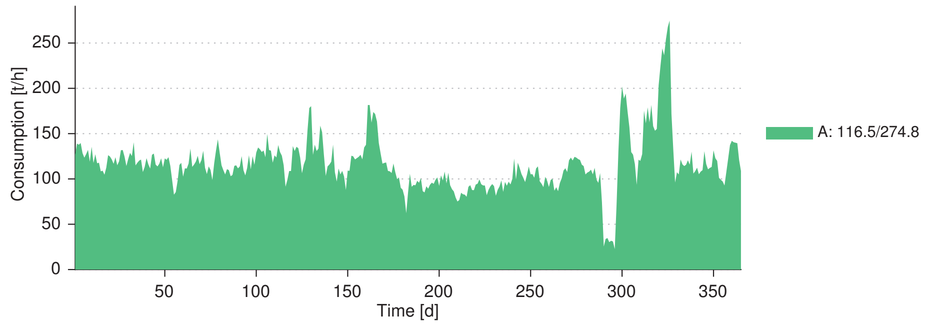



Figure 2.10 – Measured 90 barg steam consumption in Site P.

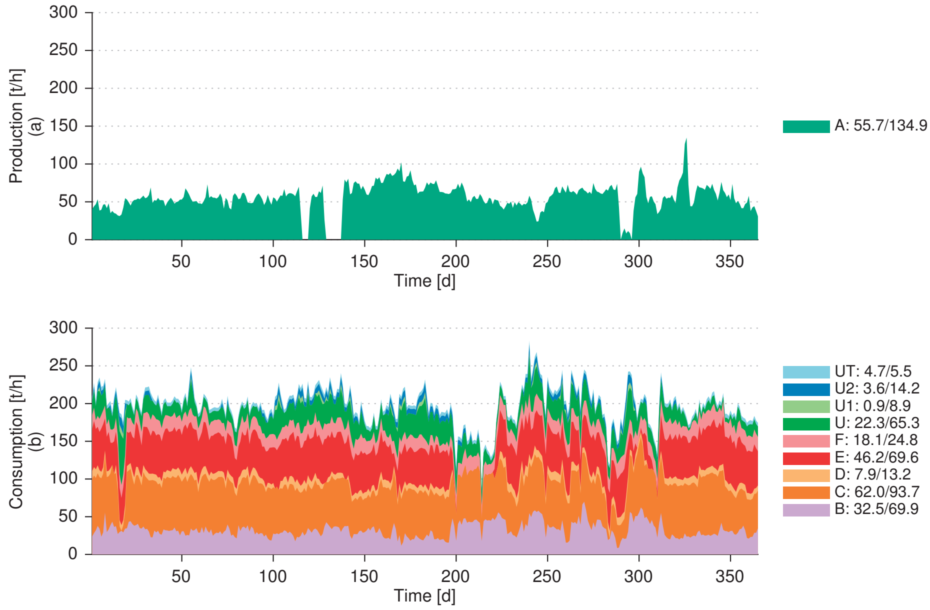



Figure 2.11 – Measured 30 barg steam production (a) and consumption (b) in Site P.

nature of the oxidation reactions. The principal consumer of 5 barg steam are the Utilities (U), reaching up to 95.7 t/h of demand. The average demand in 5 barg for Site P is 66.0 t/h with a peak value of 148.1 t/h.

The activation of the condensation turbine and atmospheric discharge can also be seen in Figure 2.12 around day 130. A high quantity of 5 barg steam is released from PU A during this period, leading to an oversupply which is dealt with by venting and condensing. A maximum of 71.8 t/h of steam is thereby released to the atmosphere.

Figure 2.13 shows an overview of the steam consumption for Site P, with the yearly trends in graph (a) and the load duration curves in graph (b). These figures highlight that the steam demand takes place at each level of the Site, with a relatively constant 90 barg and 30 barg


Figure 2.12 – Measured 5 barg steam production (a) and consumption (b) in Site P.

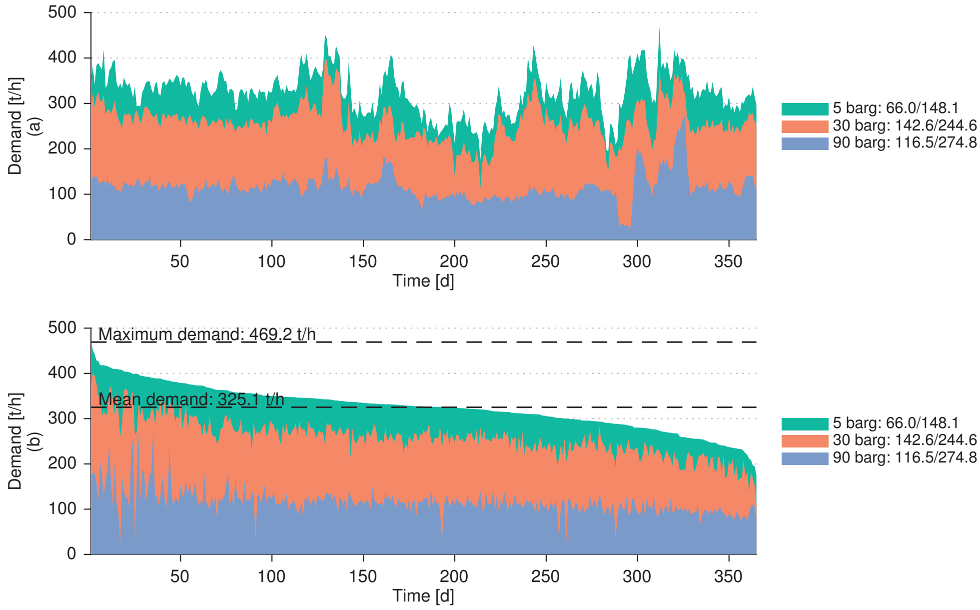



Figure 2.13 – Measured steam demand overview for Site P.

steam demand. High 90 barg steam demand generally leads to high overall demand. This trend is typical of a petrochemical site, as PU A, the cracker is the only consumer of 90 barg steam.

High cracker production (requiring higher 90 barg steam consumption) leads to higher production rates in the downstream PUs and therefore higher overall steam consumption. The mean and maximum demands for Site P are respectively 325.1 t/h and 469.2 t/h.

The design installed capacity of Site P is 390 t/h (3 × 130 t/h), meaning that at peak demand it must import 84.8 t/h of steam from the Central Boilerhouse. Similarly to Site R, an offline boiler in Site P would imply the necessity to import steam from the Central Boilerhouse.

### 2.3.3 Overall demand

Figure 2.14 shows the overall steam demand for the TIC in graph (a) and the load duration curves in graph (b). The mean overall demand is 480.2 t/h with a peak value of 624.9 t/h on day 312. The figures clearly show that the steam demand in Site P is much larger than that of Site R. Site R's steam demand is dominated by 20 barg steam consumption, while Site P consumes important amounts of steam at each of its pressure levels. Table 2.9 shows the key properties of the TIC's steam demand.

Table 2.9 – Measured total steam demand overview

| | Installed | All levels [t/h] | | 90 barg [t/h] | | 20/30 barg [t/h] | | 5 barg [t/h] | |
|---|---|---|---|---|---|---|---|---|---|
| | | Mean | Max | Mean | Max | Mean | Max | Mean | Max |
| Site R | 180 | 155.1 | 192.8 | 0.9 | 21.1 | 138.4 | 180.2 | 15.8 | 43.6 |
| Site P | 390 | 325.1 | 469.2 | 116.5 | 274.8 | 142.6 | 244.6 | 66.0 | 148.1 |
| CB | 260 | | | | | | | | |
| Total | 830 | 480.2 | 624.9 | 117.4 | 273.1 | 281.0 | 412.4 | 81.9 | 163.4 |

As the industrial sites operate independently, their peak demands take place at different times. The total installed steam production capacity of the TIC is 830 t/h meaning that there are always operating reserves. The analysis of the steam demand per site has shown that the operating reserves offered by the Central Boilerhouses' steam production capacity is crucial to the proper operation of the site.

## 2.4 Aero and water cooling

Process cooling is required in both sites, usually for cooling after separation or to remove heat from exothermic reactions. The principal utilities used for cooling are aero and water cooling. Identification of the cooling requirements of an industrial site is an important step towards carrying out energy efficiency and integration studies such as Total Site Analysis as heat may be available for recovery.

Some causes of cooling requirements are detailed below:

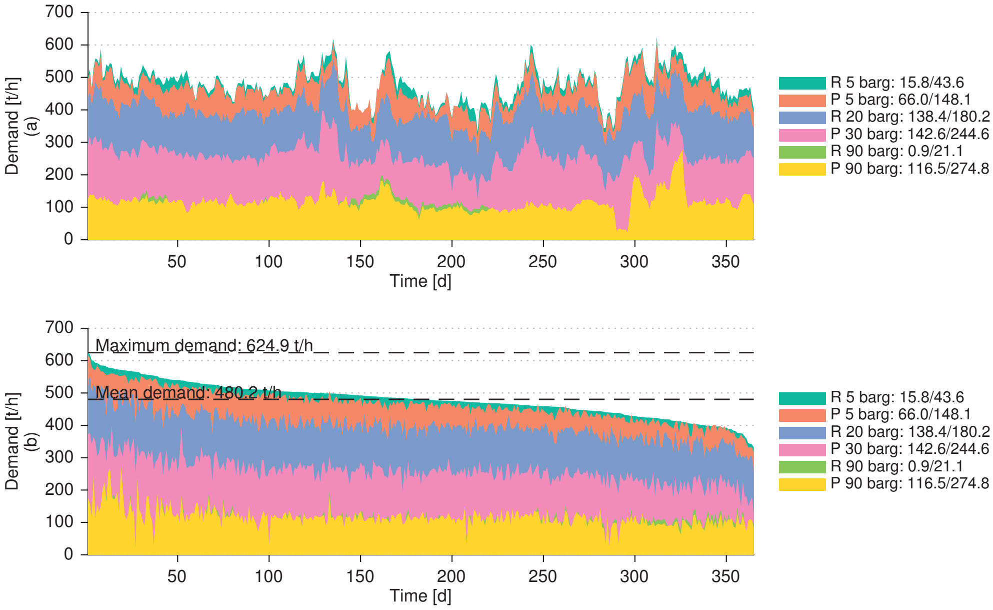



Figure 2.14 – Measured steam demand overview for the Cluster.

- Cooling after separation. Distillation columns are heated using reboilers at their base, allowing for the evaporation and therefore distillation of different fractions of products. Much of the heat contained in these fractions can be integrated (used to heat other streams) and therefore reduce the overall heating requirements, though this is not always done. Cooling after separation refers to the cooling of process streams once they leave distillation columns. These streams may require cooling before entering their next PU, or so as to be stored and transported.

- Exothermic reactions, lead to an important production of heat, especially in petrochemical sites where polymerisation and oxidation reactions take place. In the case of oxidation, steam can be generated using the excess heat, though this is rarely possible in polymersiation due to the relatively low temperature of reaction.

- Crackers often produce significant amounts of high temperature heat as a result of exothermic reactions or furnace operations. Steam may be produced from this heat, contributing towards reduced heating and cooling demand.

Table 2.10 shows the mean and maximum cooling demand for each of the TIC's PUs. The time-series of cooling demand for both sites is shown in Figure 2.15.

The cooling demand of Site R is dominated by the main separation unit (PU A) and the crackers (PUs C and D). Cooling demand falls as a consequence of PU D going offline.

Table 2.10 – Cooling demand for Sites R and P.

| | Water cooling [MW] | | Aero cooling [MW] | |
|---|---|---|---|---|
| | Mean | Max | Mean | Max |
| **Site R** | | | | |
| Unit A | 5.3 | 8.1 | 19.1 | 28.7 |
| Unit B | 5.4 | 7.8 | 7.3 | 10.8 |
| Unit C | 8.8 | 18.4 | 15.0 | 22.5 |
| Unit D | 9.0 | 26.2 | 6.2 | 15.8 |
| Unit E | 7.2 | 14.9 | 3.8 | 5.2 |
| Unit F | 12.4 | 18.4 | | |
| Total | 48.1 | 77.1 | 51.4 | 75.3 |
| **Site P** | | | | |
| Unit A | 70.7 | 102.4 | 65.2 | 71.3 |
| Unit B | 22.3 | 26.9 | 4.0 | 4.6 |
| Unit C | 3.9 | 5.4 | 19.2 | 24.2 |
| Unit C | 7.1 | 7.7 | | |
| Unit E | 11.6 | 14.9 | 2.9 | 4.2 |
| Unit C | 21.7 | 24.0 | 27.0 | 29.8 |
| Total | 137.2 | 173.2 | 118.3 | 129.4 |

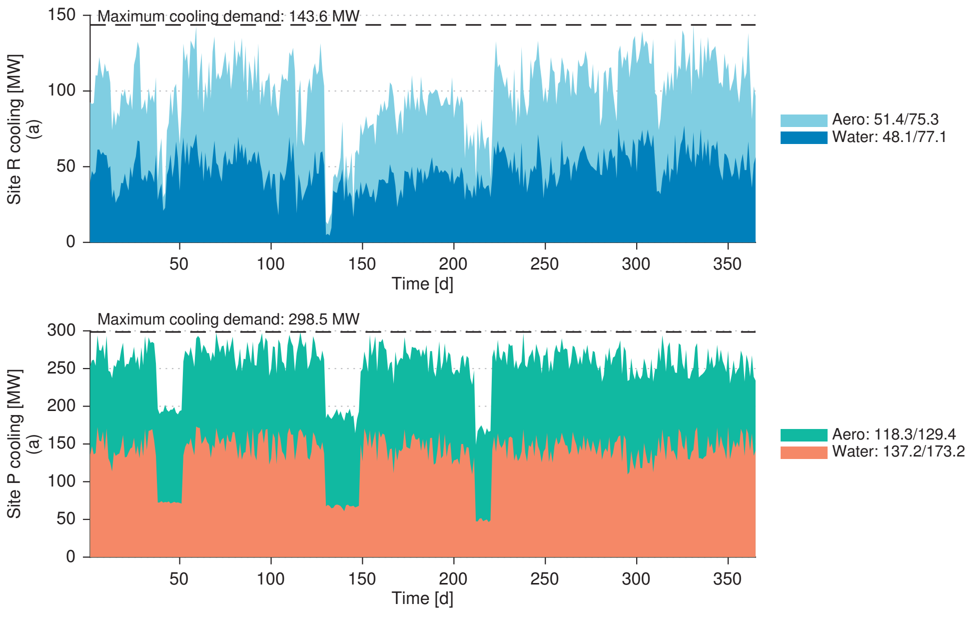



Figure 2.15 – Cooling demands of Site R (a) and Site P (b).

The cooling demand of Site P is dominated by the cracker (PU A), the oxidation plant (PU E) and the polymerisation unit (PU F). The major variations in the demand are caused by PU E shutdowns. As PUs A and F operate quite constantly throughout the year, a cooling water baseload can be seen at around 140 MW. The aero cooling demand is mostly driven by PUs A and E. The shutdown of PU E on three occasions can clearly be observed.

The difference in cooling requirements between the two sites clearly reflects the highly exothermic nature of petrochemical reactions, especially oxidation and polymerisation.

## 2.5 Operational constraints

As the products of a PU are often the feedstock of others, PUs become interdependent. Furthermore, certain PUs can be considered as critical for the industrial site, their shutdowns should therefore be avoided at all costs. Events leading to PU or utility shutdowns typically include shortages in feedstock, steam or electricity.

For example, the main crude separation unit provides the feedstocks for all the other refining units. As little storage is available for intermediate products, a shutdown of PU A in Site R means that most other PUs must follow suite.

For the above mentioned reasons, operators have elaborated load shedding procedures in the facing of specific events. These describe the order in which PUs can be shutdown leading to reducing utility demand. For example a shortage of electricity will not be dealt with in the same manner as a shortage of steam. Non-critical units will be shutdown first, turbines may be deactivated in favour of letdowns coupled to desuperheaters and critical units will only be shutdown when all other options are exhausted.

Unit shutdowns can be associated to a financial penalty, corresponding to the lost profits resulting from unit shutdown. This value may be complicated to calculate as costs are dependent on the market. Estimates can be made for this value, though in reality an in-depth market and financial analysis may be necessary.

Table 2.11 shows the steam load shedding order for each of the PUs and utility demands in the TIC as well as the penalty costs associated to disturbances from PU shutdown. For the turbines $P$ corresponds to the generation of electricity by the turbine. Disturbances to the steam network may include unexpectedly high steam demand or boiler maintenances and failures. Electrical disturbances are not covered in this work.

Several units may have the same shedding order, which means that operators can choose between them or deactivate all of them. Some units are not given shedding orders or penalty costs as they are considered too critical to shutdown. Seven shedding priority levels are defined for Sites R and P though any number could be chosen.

## 2.6 Losses

Material and energetic losses can take place for any number of reasons on industrial sites. The cases of thermal, steam and other light losses are described below. Heavy material losses as they are exceptional in nature.

Table 2.11 – Operational constraints for Sites R and P.

| | Steam shedding order | Penalty cost [$/h] |
|---|---|---|
| **Site R** | | |
| Unit A | 6 | 20000 |
| Unit B | 4 | 11200 |
| Unit C | 5 | 27600 |
| Unit D | 7 | 29000 |
| Unit E | 7 | 28000 |
| Unit F | 3 | 14400 |
| Utilities (U) | 7 | 28000 |
| Utilities (U1) | 2 | 12000 |
| Utility Turbines (UT) | 7 | 12000 |
| Turbine RT1 | 1 | 86 $\times Flow_{RT1}$ |
| Turbine RT2 | 1 | 86 $\times Flow_{RT2}$ |
| **Site P** | | |
| Unit A | 7 | 30000 |
| Unit B | 5 | 20000 |
| Unit C | 5 | 3000 |
| Unit D | 3 | 5600 |
| Unit E | 6 | 40000 |
| Unit F | 6 | 30000 |
| Utilities (U) | 7 | 30000 |
| Utilities (U1) | 2 | 2400 |
| Utilities (U2) | 4 | 2400 |
| Utility Turbines (UT) | 7 | 30000 |
| Turbine PT1 | 1 | 106 $\times Flow_{PT1}$ |
| Turbine PT2 | 1 | 57 $\times Flow_{PT2}$ |

### 2.6.1 Thermal losses

Figure 2.16 shows several examples of thermal losses identified during an thermo-imaging survey of an industrial site. The pictures in (a-c) show thermal losses in utility pipes while (d-f) show thermal losses from PUs. Each picture is briefly described below.

(a) Thermal losses from temperatures reaching 135 °C in steam pipes indicating bad insulation. Hotspots often occur in valves where thermal losses can be very high

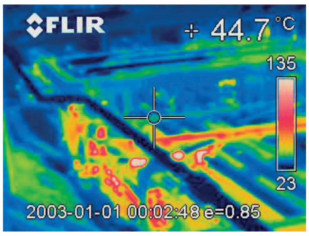
(b) Thermal losses from temperatures reaching 118 °C in steam pipes indicating bad insulation.

(c) Thermal losses from temperatures reaching on a process pipe, reaching 73 °C. Process fluids often leave PUs at relatively high temperatures, either to be cooled for storage or reheated when entering the next PU. Improved insulation reduces the heating requirements.

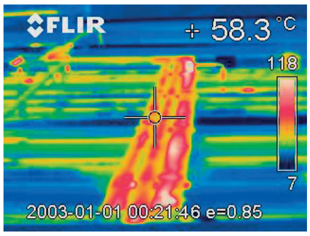
(d) Image of the body of a distillation column, reaching 118 °C, likely at a process stream drawoff. Thermal losses in a column must be compensated through reboiling in the bottom.

(e) Image of a distillation column and process stream drawoff at its head, with a peak temperature of 120 °C. Process heat could be conserved and integrated to reduce overall energy costs.

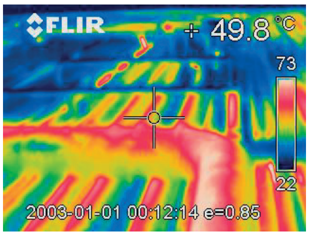
(f) Image of a furnace and its chimney. Given the low resolution of the picture it is likely that hot spots higher than 73 °C would exist. The image highlights that thermal losses take place all over a PU.



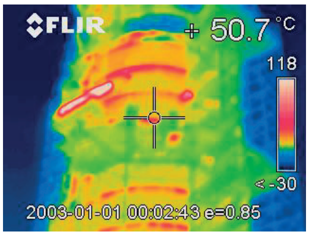

(a) Pipe rack 1



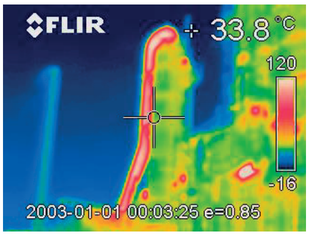

(b) Pipe rack 2



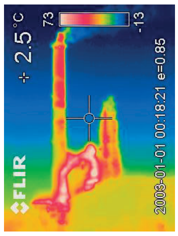

(c) Pipe rack 3




(d) Distillation column body




(e) Distillation column head




(f) Chimney & furnace

Figure 2.16 – Thermal imagery of an industrial site.

Thermal losses in steam pipes imply that the steam will inevitably start to condense, steam traps are therefore installed to recover condensed steam and limit corrosion, reduce steam hammer effects and improve the steam quality [21]. Steam traps are necessary even in the most well insulated steam network as thermal losses cannot be avoided.

### 2.6.2 Steam losses

Figure 2.17 shows six examples of material losses in a steam network. Image (a) shows a steam leak due to a ruptured pipe, while (b) shows steam billowing through a leaky seal. It is difficult to establish the source of the leak in Image (c) though it seems to occur near a valve. The impressive leak in Image (d) offers equally ambiguous information.

Image (e) of Figure 2.17 shows a steam trap venting to the atmosphere. The steel pipes behave like heat exchangers with the atmosphere and the steam within is cooled, a fraction of which will condensate. It is difficult to know if the steam trap is properly functioning and releasing flashed condensate to the atmosphere or if it is broken and releasing good steam to the atmosphere.

Given that steam traps can be numbered in the thousands and that pipes cannot be perfectly insulated, efforts can be made to reduce losses through proper choices in material and maintenance operations.

To reduce demineralised water losses, steam traps should be connected to the condensate return network. Steam released to the environment poses no human threat once it has dissipated, though the economic cost of demineralised water can be important. Table 2.12 shows the mean estimated properties condensed steam and steam leaks.

Table 2.12 – Identified leaks for Site R (a) and Site P (b).

| | Condensend steam [t/h] | | Steam leaks [-] | | Leak flowrate [kg/h] | |
|---|---|---|---|---|---|---|
| | 20/30 barg | 5 barg | 20/30 barg | 5 barg | 20/30 barg | 5 barg |
| Site R | 2.0 | 1.5 | 45 | 77 | 150 | 50 |
| Site P | 1.0 | 1.5 | 62 | 53 | 180 | 50 |

Monthly values of the number of identified steam leaks are shown in Figure 2.18. Condensate values are considered constant throughout the year despite the varying external temperature. No 90 barg steam losses are considered in the TIC as they are usually dealt with very rapidly given their extraordinarily rare nature and very high impact.

### 2.6.3 Other losses

Losses on other utilities are likely to occur, typically on the compressed air and pressurised water networks. As water can cause important damage due to flooding, leaks should be plugged as fast as possible.

(a) Ruptured pipe. (b) Leaky seal.

(c) Leaky valve. (d) Unidentified leak.

(e) Billowing steam trap. (f) Dramatic picture.

Figure 2.17 – Steam leaks in industrial sites.

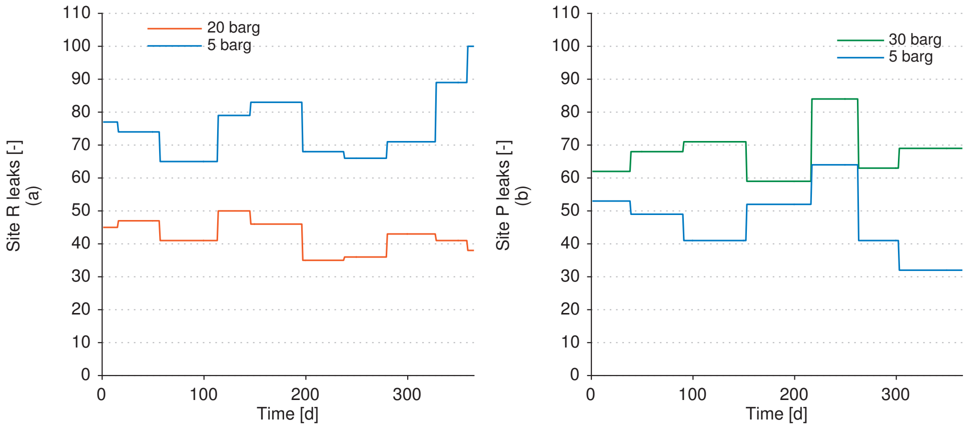



Figure 2.18 – Number of steam leaks in the Typical Chemical Cluster for year 2014.

Other high value utilities such as natural gas, off-gas, hydrogen, nitrogen and sulphuric acid can be extremely dangerous (explosive and toxic) and are monitored through gas sensors. Leaks generally lead to partial or total site confinement while the source of the flows are stopped and time is given for the gases to disperse. These events are rare in comparison to steam leaks, with very short resolution times.

## 2.7 Conclusion

This chapter has described several aspects of a refining and petrochemical cluster, the TIC. Particular attention was paid to the steam network of the TIC, with details about the aero and water cooling demand as well. The data collected corresponds to the minimum required to carry out a Total Site Analysis or to optimise a steam network.

The architecture of the steam networks of the refining (Site R) and petrochemical (Site P) sites making up the TIC were detailed, as well as their PUs. More details about the internal steam networks of the PUs can be found in Appendix A.

A brief analysis of the steam production and consumption by the sites of the TIC reveals that mass balances do not close on any of the steam headers. This is due to unaccounted consumers and losses as well as inaccurate steam flow measurements, stemming from unavoidable measurement error. The steam losses of the TIC are considerable though as of yet unquantified. This point will be addressed in Chapter 3.

A first step towards optimising the energy use of an industrial site must be to close the mass and energy balances of the system, so as to ensure a proper understanding of it and measure the impact of energy efficiency solutions. This is the focus of Chapter 3.

The aim of the TIC is to improve understanding about such clusters and to have a reference for all the case studies of this work. Data was chosen so as to be representative of the possible variations in the years to come and therefore to permit the analysis of energy efficiency solutions.

The TIC must undergo important investments within the coming years to replace the ageing CB boiler. The case studies in the chapters to come will focus on preparing its data and the tools necessary to optimise its energy efficiency and establish resilient investment options.

# 3 Data reconciliation in the Refining and Petrochemical industry

*This chapter presents a methodology to improve the data quality of measures in steam networks and calculate their unknowns thermodynamic propoerties.*

## 3.1 Introduction

Precise data and good process knowledge are required to carry out quality energy efficiency studies. Closing mass and energy balances are therefore a first step in this direction as they reveal the depth of process knowledge and shed light on unknowns. This assures that all flows in and out of a Process Unit (PU) are accounted for and thermodynamically quantified.

When dealing with open mass balances, standard industry practises include calculating differences between measured and unmeasured flows, using estimates when necessary, attributing remaining differences to losses and manipulating data. While conveniently simple, these methods treat the symptoms of the problems rather than the causes, some of which are listed below:

- Unmeasured flows and thermodynamic states: Measurement devices can be expensive and cumbersome meaning that their numbers will be limited according to financial concerns and technical feasibility.

- Measurements errors: No measurement device is perfectly accurate and its readings contain random and systematic errors [36].

- Measurement system errors: Signal transmission, sensor calibration, power fluctuations and data storage each contribute noise and errors to original measurements, adding inaccuracies to them.

- Assumptions: In the absence of measures, assumptions about thermodynamic states of flows may be necessary though results may be uncertain.

A secondary effect of closing mass balances using simple arithmetic rules is that of permanently reducing process knowledge. It may shed light on the 'known unknowns' such as estimates, but nullifies the existence of 'unknown unknowns'. These can include occasionally used flows for example steam hoses or consumers that have been forgotten over times such as pipe tracing.

Lastly, all energy studies require data to have a high level of certitude. Operational optimisation studies require precision, as even a small difference in overall energy consumption can amount to important financial gains. Benefits of solutions can easily be drowned in the noise of an inaccurate measurement system. Similarly, infrastructure optimisation studies require precise data so as to meet the requirements of investment strategies, for example very short pay back times.

### 3.1.1 State-of-the-art

In view of the aforementioned data issues which are a constant in the process industry though they may go unnoticed, Data Reconciliation was developed as a methodology to improve the quality of measures, to validate or correct assumptions and provide more rigorous ways to estimate unknowns.

With advances in computing, Data Reconciliation was developed by Kuehn and Davidson in 1961 [25] based on the least square principle. It was introduced to the process industry by Reilly and Carpani in 1963 [26] to improve material balances in process plants and therefore process knowledge. Developments in the areo of gross error detection have also been extensively covered [46]. Data Reconciliation has become a trusted tool among the following industries:

1. Refineries [27], Chemical sites [29], Petrochemical sites [31]: Improved process knowledge, product accounting, utility network accounting.
2. Oil and gas extraction: Improved estimation of reservoir sizes and multiphase flowrates and properties (virtual flowmeters) [32].
3. Nuclear power plants: Ability to push steam turbine production to its upper limits through improved process knowledge, increased security through better process knowledge and added measurement redundancy [33].

While developed for steady state operations, recent advances have attempted to apply it to dynamic states through the recycling of previous reconciliation results [48] or through direct multi-period Data Reconciliation [47].

### 3.1.2 Objectives

These developments provide sufficient tools to reconcile the mass flows and thermodynamic states of industrial sites, however little guidelines exist on how to best apply them to large problems. This work therefore addresses this need by proposing a systematic methodology to reconcile data in the refining and petrochemical industries, calculate unknowns (such as losses) and close mass and energy balances.

The chapter firstly explores common data issues concerning steam networks in the refining and petrochemical industry in Section 3.2. This is followed by a methodology to model and reconcile most steam flow types that can be encountered in this industry in Section 3.3.

The methodology developed is also presented in more detail in a Technical Report *Data Reconciliation of steam networks in the refining and petrochemical industries.* [45].

## 3.2 Industry data issues

Some typical data issues faced by the refining and petrochemical industries are presented below, followed by their causes.

### 3.2.1 Example from the Typical Industrial Cluster

In the case of the Typical Industrial Cluster (TIC), mass and energy balances do not close as measurement errors are present and not all flows are measured. The 90 barg header of Site R is used as an example in Figure 3.1, showing the producers and consumers of steam in the header with their mean thermodynamic properties. Measures are shown in black while red values correspond to calculations.

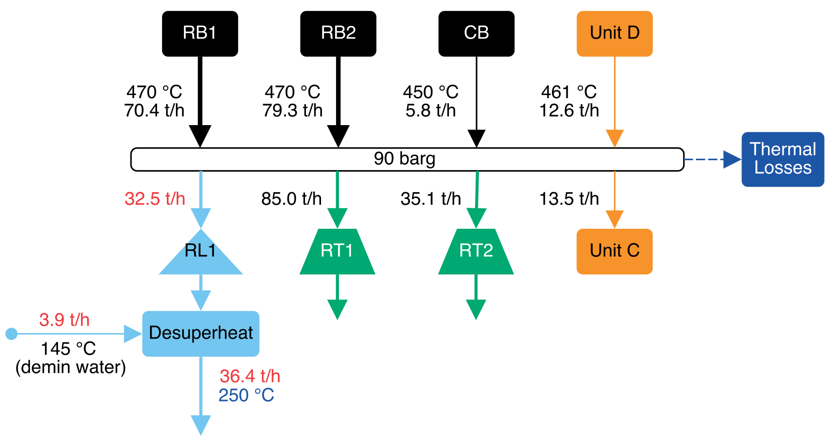



Figure 3.1 – Mean Site R 90 barg header mass balance.

The temperatures, pressures are only measured for the producers. The flowrates are all measured with the exception of the letdown RL1 (value calculated by difference). The demineralised water usage is estimated at 3.6 t/h using the available thermodynamic properties (desuperheating temperature setpoint and demineralised water temperature).

All steam consumers and producers are represented in this figure and engineers have guaranteed that no high pressure steam leaks occurred over the chosen period.

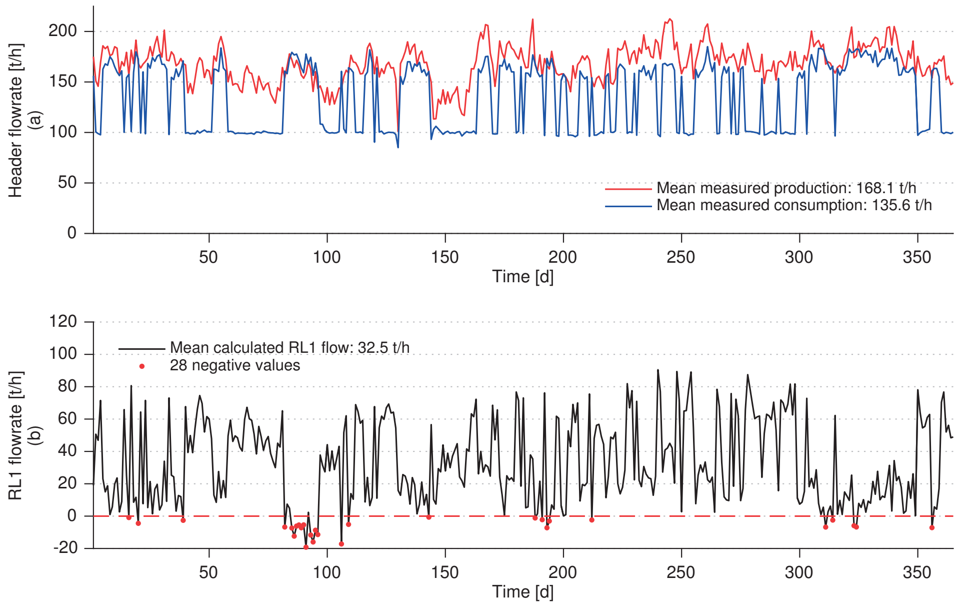



Figure 3.2 – Measured steam 90 barg production and consumption (a) and calculation of RL1 letdown flowrate (b).

Figure 3.2 shows the sum of the inlet and outlet steam in the 90 barg header of Site R (a) and the calculated flowrate of the letdown RL1 in (b) (calculated by difference). In (b) we see that a simple mass balance difference is not sufficient to accurately calculate the flowrate through the letdown, as values become negative on 28 occasions, which is physically impossible.

While the occurrence of negative values is relatively small (7.7% of time), they highlight the fact that random or systematic measurement errors are always present on this header.

This issue repeats itself on all headers and is worsened at lower pressures as a smaller proportion of flowrates are measured and assumptions become necessary. Data Reconciliation on measures and assumption validation is therefore necessary before optimisation can be attempted.

### 3.2.2 Causes of open mass balances

The three main causes for the identified data issues are a high number of unmeasured consumers, low measurement accuracy and steam losses. These are briefly described below, followed by an example of their combined effects.

#### Unmeasured consumers

As steam was historically considered a cheap utility, many steam consumers were left unmeasured in favour of using arithmetic to close mass balances, avoiding expensive measurements devices. Several typical cases are described below:

- Letdowns: Flowrates through letdowns are often left unmeasured, as they are not labelled as steam consumers, but rather transporters of steam across pressure levels. As a consequence, steam headers often lack enough measurements to be redundant.

  Though steam flows through letdowns are rarely measured, the demineralised water injected through the desuperheaters is at times measured. If the temperatures and pressures of the inlet and outlet steam are measured, as well as the demineralised water flow, the initial letdown flow can be back calculated using thermodynamic relations.

- Turbines: Unlike letdowns, turbines produce useful mechanical work, to power electricity generators, fans, pumps and compressors. Larger turbines are usually measured as their work is critical for PUs or for the industrial site.

  On the other hand, smaller turbine complexes (for example turbo-pump and turbo-compressor) are often left unmeasured or are bundled together into one measure. Within PUs, turbine flowrates are generally not measured though their activation status can be obtained through discussion with operators or through data systems.

- Consumers: Given the very large number of small steam consumers on industrial sites, it would be prohibitively expensive to measure all of their flows and properties. These 'known unknowns' include:

  - Utility tracing: Pipe heating to keep fluids from congealing. Design values may give an estimate of the flowrates, though this information can often be hard to find.
  - Small heat exchangers: Small heat exchangers may not be measured. Similarly, column reboilers are not always measured.
  - Occasional consumers: heat exchangers only used at process startups, shutdowns or under specific and occasional circumstances. Their flowrates may simply not be worth calculating, as they are often manually activated with relatively small demand in steam.

  'Unknown unknown' steam consumers pose another problem. Taking the example of a steam hose used to keep equipment warm in winter: These hoses are manually activated for known or unknown periods of time. Their design flowrates may be known, but these values cannot be certain. Neglect of these uncounted devices makes calculating their flowrates very challenging.

- Producers: Most steam producers are measured as their flowrates are usually significant. Furthermore as they play a role in process cooling, it is important for operators to be able to monitor their effectiveness.

The case of flash steam from recovered medium pressure condensates is challenging as the condensate flowrates and properties are often unmeasured. Operators may use rules of thumb based on design values to estimate their flowrates and that of the flash steam.

### Low measurement accuracy

While electricity is simple to measure to a high degree of accuracy, the same does not apply for steam or gases (as they are compressible and subject to change according to pressure, temperature and composition). Orifice plate devices make up the large majority of the steam flowmeters in the refining and petrochemical industry, while the more accurate vortex flowmeters are reserved for transactionable or critical flows.

Measurement devices inherently suffer from random and systematic errors, as do their sensors and the entire metering system. Proper maintenance can reduce the effects of systematic errors, for example in orifice plate devices where the sharp edges of the orifices plate devices are blunted with time leading to reduced accuracy [38]. Random errors can be reduced through high quality devices, though they can never be eliminated.

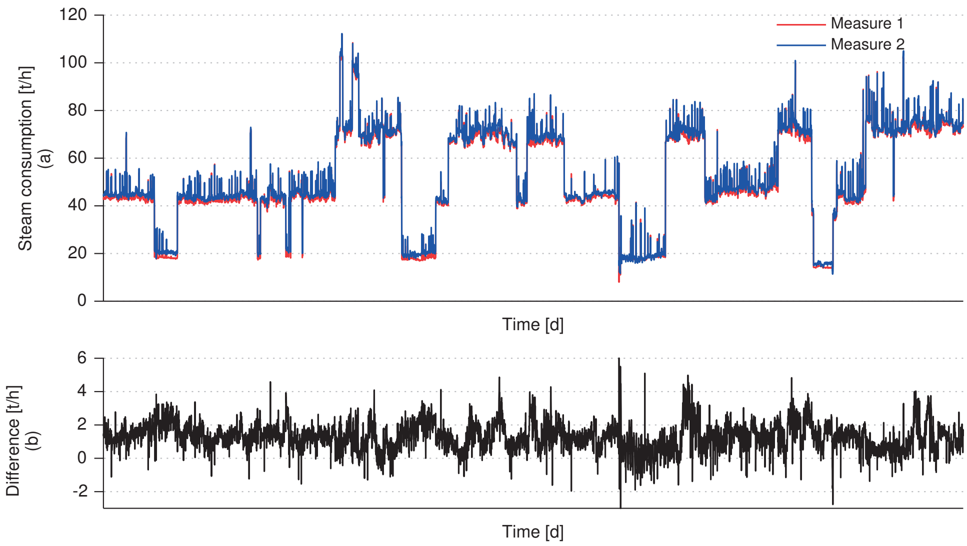



Figure 3.3 – Example of measurement error on a single flow meter.

- Random errors: Random errors are ever present and unpredictable in all measuring devices. They should not affect the accuracy of measures averaged over large periods of time (the mean should be equal to zero). In high accuracy work, random errors tend to gain importance as over short periods of time and their effects can be significant.

An example is given in Figure 3.3, which shows two readings on the same steam flow. As the steam is bought and sold, a measure is made by each actor to ensure redundancy and oppose any eventual accounting irregularities. The graph in (a) shows both measurements while (b) shows the difference between the two with a mean value of 1.3 t/h. Some fairly significant differences ($\pm$ 6.5 t/h) can also be seen at times. Many of the variations can be explained by random errors.

Considering a steam price of 18 $\$/t_{steam}$, an accounting difference of 205,000 \$ is present over a year of measures.

- Systematic and gross errors: A systematic error is "*a persistent statistical error having a non-zero mean that cannot be attributed entirely to chance but to inaccuracy inherent in the statistical system*" [39]. Though their importance may vary, systematic errors can skew and shift data, making mass balances complicated to calculate even when using lengthy time averages.

  These errors may stem from calibration issues (leading to a positive or negative shift in measured values, as seen in Figure 3.3) and multiplier effects causing data readings to no longer correlate with real data.

  Gross errors correspond to situations where measurement devices or associated sensors are not functioning properly and give rise to readings far away from the real state.

  Electronic sensors are calibrated for specific operating ranges and may give gross errors outside of those ranges. Figure 3.4 shows the consequence of a badly programmed sensor, leading to an overscale measurement. In this example, the steam flow obviously surpasses the scale limit of the sensor. As such, a significant proportion of steam cannot be quantified.

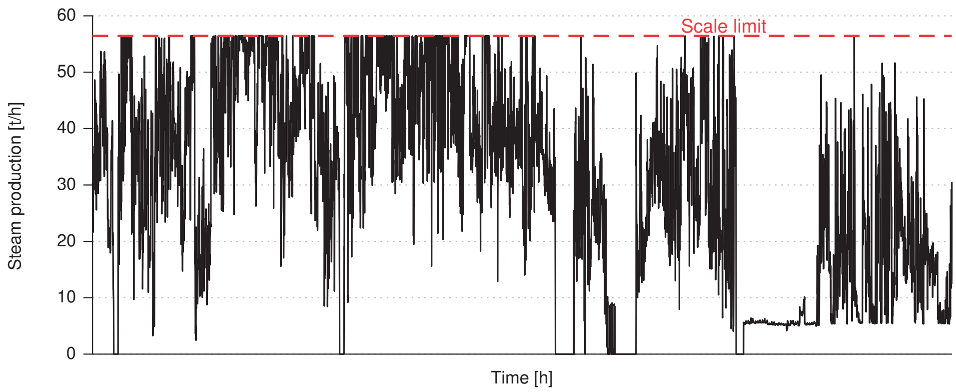



Figure 3.4 – Example of an overscale measurement.

Figure 3.5 shows another case of false readings in which steam is incorrectly attributed (and billed) to a process. Graph (a) shows the steam consumption of a heat exchanger over 41 days. Graph (b) shows the controller output of the control valve associated to the steam flowrate. Graph (c) shows the throughput of feedstock through the PU. The segment shown in red corresponds to a total PU shutdown which lasted 10.5 days. Graphs (b) and (c) corroborate this information.

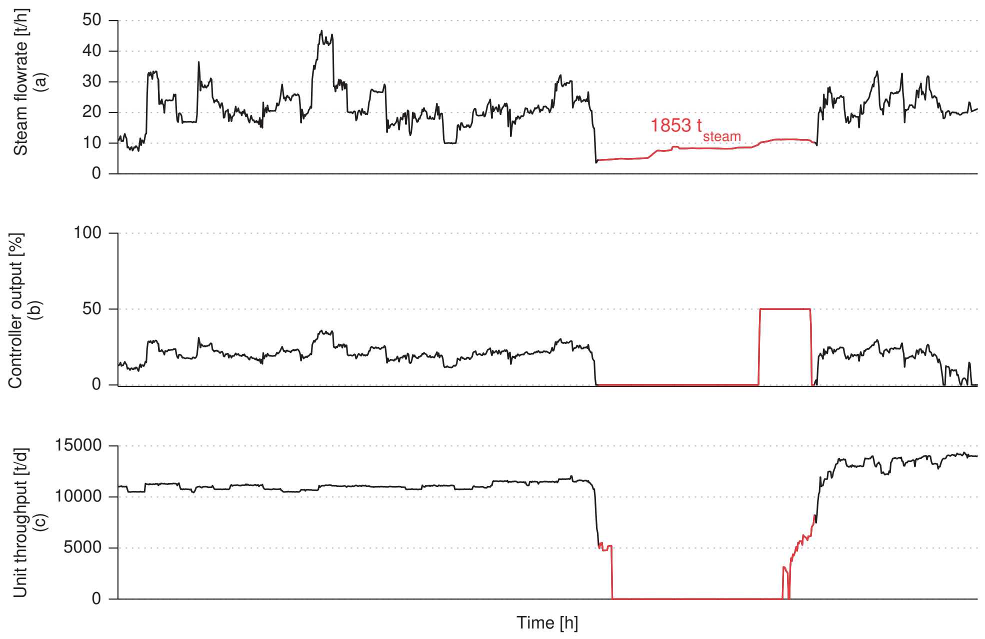



Figure 3.5 – Example of the incorrect measurement of a steam flow PU shutdown.

The figure shows that despite the PU being completely shutdown, 1853 tons of steam are incorrectly attributed to the heat exchanger, corresponding to 33,000 \$ (18 \$/$t_{steam}$). The PU is billed for this steam and energy studies may incorrectly consider this steam consumption. Such errors occur as a result of the sensor electronics' behaviour.

Lastly, pressures, temperatures, densities and composition of flows may change with time, measurement devices operating outside of their defined ranges [41] may therefore deliver erroneous values. These numerous cases highlight that proper calibration and maintenance of measurement devices is necessary on industrial sites.

### Losses

- Condensation losses: As steam flows through a pipe, it will inevitably loose some of its energy through radiation. Steam condensation follows and the condensates must be evacuated for safety and quality reasons. A functioning steam trap will evacuate condensates when they accumulate within pipes, though a malfunctioning one may evacuate no condensate or on the contrary evacuate good steam constantly.

  It is difficult to know whether or not a steam trap is working properly as in either case flash steam is vented to the atmosphere. Proper maintenance operations are therefore necessary to manually inspect steam traps.

Extreme weather events such as heavy rains can lead to significantly increased condensation losses, as the ground on which pipes are installed can be flooded. In such cases, pipes can be completely submerged and substantially cooled.

- Steam leaks: Steam leaks are inevitable though they may be addressed through proper maintenance. They are caused by corrosion of steel pipes and their joints as seen in Section 2.6. The larger the industrial site, the more significant the proportion of steam losses will be as networks become more complex and more expensive to manage.

### Error combinations

Figure 3.6 shows the combined effects of the above mentioned points. Graph (a) shows the inlet of steam into a header in red and the outlet in blue, while (b) shows the difference. In this header, all of the inlets and outlets of steam are measured, therefore the mass balance should theoretically close. In general the trends of the inlet and outlet are the same, though some gross errors appear to be present:

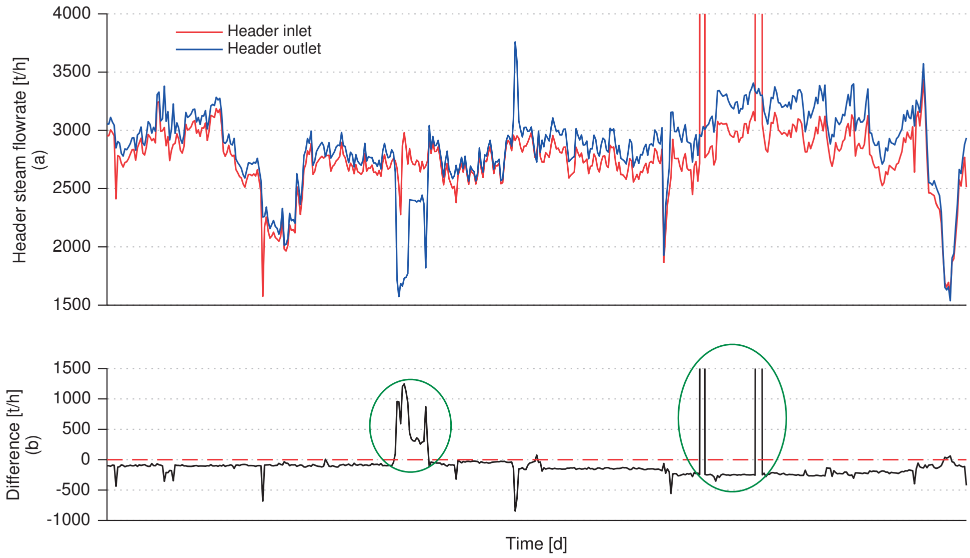



Figure 3.6 – Example of the effect of combined errors on mass balances.

- Negative difference: Random errors (noise), systematic errors (calibration and sensor failures) are the major reasons for negative mass balance differences.
- Positive difference: Losses (steam leaks and condensation losses) must be comparatively small in this example as the difference is rarely positive. The same applies to random errors. On the other hand, sensor failures are visible in the circled areas of (b). In the left circle, it appears that a consumer's measurement device goes offline, while in the second circle out of scale values are reported on two occasions, likely due to sensor malfunction.

Such data necessarily requires treatment before it can be used in an engineering study. Impossibly high values corresponding to gross errors. must be filtered to avoid influencing the averages and mass balances must be closed. When combined to filtering techniques to eliminate gross errors, Data Reconciliation offers a rigorous way to improve the quality of the data.

## 3.3 Methodology

The principles of Data Reconciliation are described in Section 3.3.1 followed by a detailed guide to modelling steam networks in petrochemical sites in Section 3.3.2, where data filtering rules are defined, followed by recommendations for modelling specific cases of steam consumption and production.

### 3.3.1 Principles of Data Reconciliation

In layman's terms, Data Reconciliation modifies the values of measurements so as to respect physical laws. Modifications are made using a mathematical optimiser which minimises the overall impact of the modifications. The physical laws in this work mostly relate to mass and energy balances.

In Data Reconciliation a new value $y_i^*$ is associated to each of the $n$ measurements $y_i$, so as to solve the system equations $F(\mathbf{x}, \mathbf{y}^*) = 0$, where $x$ are the unknowns of the system. The system equations can include mass and energy balances, chemical reactions, stochastic relations or user defined equations.

Data Reconciliation calculates $y_i^*$ by minimising equation 3.1 using a non-linear solver. This equation is also known as the Penalty.

$$Obj = \min_{x,y^*} \sum_{i=1} \left(\frac{y_i^* - y_i}{\sigma_i}\right)^2 \qquad s.t. \quad F(x, y^*) = 0 \tag{3.1}$$

$\sigma_i$ represents the uncertainty associated to measure $y_i$. In this way the sum of the squared differences of the modifications to the data is minimised. $y_i^*$ is kept as close to $y_i$ as possible, weighted by its uncertainty $\sigma_i$.

High Penalty values resulting from equation 3.1 should be investigated and understood as they may result from modelling errors or gross errors in the data.

Data Reconciliation problems must be redundant to solve unknowns and reconcile measures. This means that the number of equations must be greater than or equal to the number of variables. Many of the equations can be generated from the architecture of the steam network, for example the mass and energy balances.

#### Choice of measure accuracies $\sigma$

For a flat measure subjected only to random noise, $\sigma_i$ can be chosen as its standard deviation, it can otherwise be based on the accuracy of the measurement system [52]. However, in industrial applications, flat measures are uncommon as thermodynamic properties vary significantly with time.

Manufacturing data of the measurement devices should supply the turndown ratio and accuracies of the readings [28]. The turndown ratio defines the operational range of a device. For example, a vortex flowmeter may have a turndown ration of 10:1, with a accuracy of $\pm$1% of the reading. This means that a reading below 10% of its calibrated nominal flowrate will provide unreliable results, and in general any reading above 10% of the nominal flowrate will be accurate to $\pm$1% of the reading.

In a first step, these values can be used for the $\sigma_i$ of measurement $i$. If the optimisation of the Data Reconciliation model is not able to converge with such values, further adjustment should be made to them.

For unmeasured flowrates, large $\sigma_i$ should be used, though their choice is entirely at the experimenter's discretion. Excessive amounts of large $\sigma_i$ values should be avoided, as the Data Reconciliation resolution matrix may become singular and unsolvable.

### 3.3.2 Modelling of steam networks in refining and petrochemical sites

To apply the Data Reconciliation concepts, the network architecture and locations of measurements and assumptions must be modelled. This allows for the system equations to be generated. Data should also be filtered to eliminate gross errors.

Several types of filters are proposed followed by a detailed instruction on how to model specific steam flow types in the refining and petrochemical industry.

#### Data filtering

Data filtering eliminates recoginsable gross errors which can lead to convergence problems in the optimisation. Given the large scale of industrial sites and the hundreds of measurement devices they can contain, a systematic method for filtering is proposed. An example of the filter parameters are presented in 3.1.

- High pass filters: Each measure (flowrate or thermodynamic property) $y$ should be subject to a high pass filter, equation 3.2, to avoid overscale readings (as seen in Figure 3.4). The high pass values $y_{max}$ should be determined through a Data Analysis (DA) and operator knowledge.

$$\text{If} \quad y > y_{max} \Rightarrow \sigma = \sigma_{max} \tag{3.2}$$

- Low pass filters: Lowpass filters can limit the innaccuracies associated to flows below their minimum rates, defined by their turndown ratios, Equation 3.3.

$$\text{If} \quad y < y_{low} \Rightarrow \sigma = \sigma_{low} \tag{3.3}$$

- Cutoff filters: Cutoff filters can also be used to force values to zero to eliminate obviously erroneous sensors as seen in Figure 3.3, equation 3.4. $y_{min}$ can be chosen based on the turndown ratio data. Other data can be used to reinforce the cutoff filters, such as PU throughput. In the case of temperature and pressure measurements, design values can be applied to $y_{forced}$ to avoid skewing thermodynamic data in a posteriori averages.

$$\text{If} \quad y < y_{min} \Rightarrow y = y_{forced} \quad \& \quad \sigma = 0 \tag{3.4}$$

- Assumptions: Assumptions can be improved by coupling them to existing information, such as the PU throughput and other process knowledge. For example, if a PU is off and receives no steam, the assumed flowrate of a consumer should also be set to zero. This is especially important for assumptions, which may not have associated filters. The uncertainty values $\sigma$ associated to each assumption must be adapted according to available information.

- Measurement boundaries: It may be possible to provide boundaries for measurements based on process knowledge. For example, boilers are bounded by minimum and maximum flowrates, from which flowrates can only slightly deviate. Similarly, a pipe of given diameter $D$ will only be able to let so much steam at pressure $p$ through. This sort of difficult to obtain information can strengthen a Data Reconciliation model, as it reduces the exploration space of the mathematical optimiser.

Table 3.1 shows some examples of parameters to be used for measurement filters in industrial sites. These values were obtained through user experience for a specific problem and should be adapted to each new problem.

Table 3.1 – Examples of filter parameters when modelling steam networks.

| | $\bar{\sigma}$ [%] | $\sigma_{max}$ [%] | $y_{max}$ [M.U.] | $\sigma_{low}$ [%] | $y_{low}$ [M.U.] | $y_{min}$ [M.U.] | $y_{forced}$ [M.U.] |
|---|---|---|---|---|---|---|---|
| Orifice plate | 8 | 15 | DA | 30 | $0.25\times\bar{y}$ | $0.1\times\bar{y}$ | 0 |
| Vortex | 4 | 8 | DA | 8 | $0.15\times\bar{y}$ | $0.05\times\bar{y}$ | 0 |
| Temperature | 2 | 10 | DA | - | - | 25°C | $\bar{y}$ |
| Pressure | 2 | 2 | DA | - | - | DA | $\bar{y}$ |

### Case modelling

Data Reconciliation requires for system equations as well as variables to be defined (see Equation 3.1). This can be done in specially designed flowsheeting softwares. Figure 3.7 displays 17 flow types identified in the steam networks of petrochemical sites and refineries. This section proposes modelling rules for these different flows, guiding users towards which data they require in order to correct measurements and calculate unknown thermodynamic states.

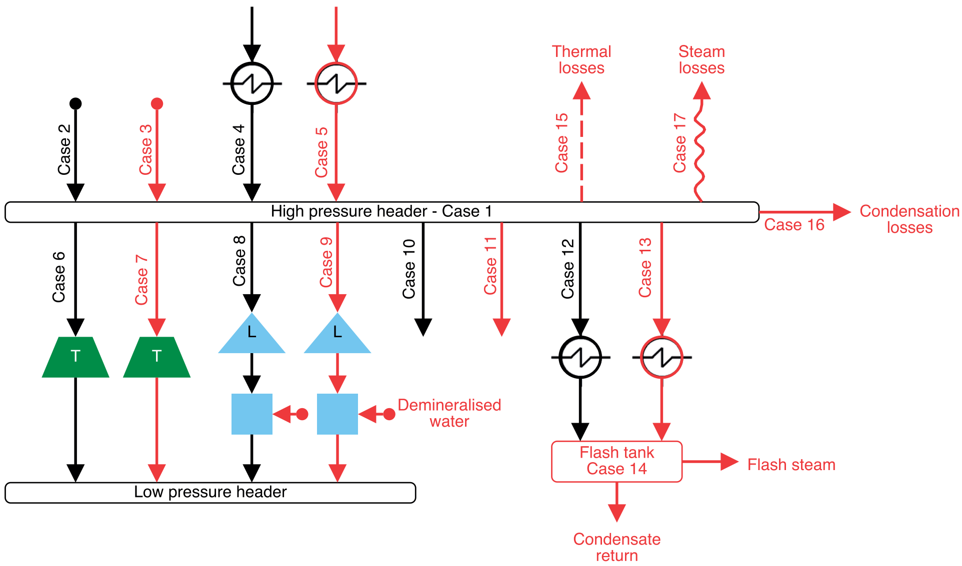



Figure 3.7 – Typical cases when modelling and reconciling a large industrial site's steam network.

Red lines indicate unmeasured states while black shows the measured ones. All cases are described in the Technical Report [45], several trivial cases are omitted below.

**Case 1 - Steam header** Steam headers should be subject to the following modelling rules [52].

1. Mass balance, Equation 3.5, where $m_i$ are the flowrates of steam belonging to header $j$ ($h_j$). The flowrates either belong to the inlet streams $h_{j,inlet}$ of header $h_j$ or its outlet streams $h_{j,outlet}$.

$$\sum_{i \in h_{j,inlet}} m_i = \sum_{i \in h_{j,outlet}} m_i \tag{3.5}$$

2. Energy balance, Equation 3.6, where $E_i$ are energetic contents of the streams belonging to header $h$.

$$\sum_{i \in h_{j,inlet}} E_i = \sum_{i \in h_{j,outlet}} E_i \tag{3.6}$$

3. Temperature equality between all outlet streams of a header, unless contradictory information exists, Equation 3.7.

$$T_i = T_{h_j} \quad \forall i \in h_j \tag{3.7}$$

4. Zero pressure drop within headers, unless contradictory information exits, Equation 3.8.

$$p_i = p_{h_j} \quad \forall i \in h_j \tag{3.8}$$

Steam is mostly superheated and therefore can be defined by its pressure level, temperature and flowrate. Condensed steam should not theoretically exist if the steam traps operate properly, though it can occur in practise. In such a case, modelling becomes very complicated as it is not possible to easily calculate the vapour fraction without high accuracy energy balances. Using rules 3. and 4. reduces the number of required temperature and pressure measurements on each header.

**Case 4 - Boilers** Modelling of steam boilers can contribute towards highly accurate measurements of the steam production. As the demineralised water network is usually measured as well, adding information from it to a boiler model adds important redundancy to steam flow calculation. Furthermore several key performance indicators related to energy efficiency can be calculated and reconciled as a result, such as the energy efficiency, economiser heat recovery, $O_2$ content and temperature of the fumes.

**Case 5 - Unmeasured steam generation** In the absence of measures on the steam flow, process side measurements can be used to calculate the energy load delivered to steam. If no process information is available, design information can be used. Without this data a statistical analysis can be carried out on the header to estimate its flowrate. If the flowrate is suspected of being significant, it is recommended to carry out manual measurements to better understand it. Possible assumptions and design values include:

- Steam: temperature, pressure and flowrate.
- Process: temperature, pressure, flowrate, composition.

**Case 7 – Unmeasured turbine flow** Data to be obtained include the following:

- Steam inlet: temperature, pressure and flowrate.
- Steam outlet: temperature, pressure.
- Turbine: isentropic efficiency.
- Moved process fluid: inlet and outlet pressure, temperatures, composition.
- Pump/compressor: isentropic efficiency.

As is often the case for smaller turbo-pump/fan/compressor complexes, few measures are available on their flows. These turbines are either activated manually or remotely. Regardless, the design flowrate $\bar{m}_{turbine}$ and isentropic efficiency $\eta_{turbine}$ should be acquired.

The outlet pressure of the steam can be assumed to be that of the lower header's, while the outlet temperature will be calculated using to $\eta_{turbine}$ and the upstream header temperature. The flowrate of the turbine is estimated using equation 3.9, where $k_{turbine}$ is the activation rate of the turbine.

$$m_{turbine} = k_{turbine} \times \bar{m}_{turbine} \tag{3.9}$$

The activation rate can be obtained as follows:

- Manual activation: empirical rules should be established for the activation rate of the turbine $k_{turbine}$. Large uncertainty should be applied.
- Remote activation: if the turbine is remotely activated, the data system should store a record of its activation through time. This data can be sampled to obtain a mean activation rate $k_{turbine}$. Large uncertainty should be applied.

The reason for high uncertainty stems from the lack of knowledge on the accuracy of $\bar{m}_{turbine}$.

If information is available about the converted mechanical power or moved fluid (in the case of turbo-compressors and turb-o-pumps), it can be used to help reconcile the original massflow. Pressures at inlet and outlet, motor efficiency, fluid composition and flowrates from the pumps or compressors would be required.

**Case 9 – Unmeasured letdown flow** Possible assumptions and design values include:

- Steam inlet: temperature, pressure.
- Steam outlet: pressure.
- Desuperheater: steam temperature setpoint, demineralised water flowrate, maximum flowrate.

- Letdown: maximum flowrate.

In the absence of measures, mass balances will help determine the steam flowrate through letdowns. If desuperheating is present, using the temperature of the letdown steam and the desuperheating setpoint as well as the mass balance differences on the lower and upper pressure levels may be sufficient information to calculate the demineralised water flowrate.

**Case 13 – Unmeasured heat exchanger** Possible assumptions and design values:

- Steam: flowrate.
- Process: temperature and pressure at inlet and outlet, flowrate, composition.
- PU: throughput, production rate, activation rate.
- Heat exchanger: surface area, heat transfer coefficient, design load, log mean temperature difference.

In the absence of measured information, design values can be associated to the PU's throughput to estimate the steam load. High uncertainty values should be chosen in such a case.

Process data can be used to calculate exchanged heat loads and back calculate steam consumption.

**Case 15 – Thermal losses** Thermal losses are ever present in industrial sites and manifest themselves by temperature decrease and condensation of steam. If the flowrate of steam is known, the thermal losses can be estimated through the temperature differential between steam inlet and outlet, or by establishing the surface area and heat transfer coefficient of the pipes. The first method is only possible if the steam's temperature remains above the saturation temperature.

**Case 16 – Condensation losses** The amount of condensed steam can be estimated based on design values of the steam network. The thermodynamic calculation is based on the diameter of the pipes, the grade of the steel, the insulation material and thickness, steam pressure and temperature.

Another method for estimating condensate losses consists in calculating mean steam trap flowrates based on their analysis (including malfunctioning traps). Once the mean steam trap flowrate $\bar{m}_{trap}$ are established, the flowrate of condensed steam can be estimated using equation 3.10, where $n_{trap}$ is the number of steam traps in the industrial site.

$$m_{cond} = n_{trap} \times \bar{m}_{trap} \tag{3.10}$$

Regardless of the method used, the uncertainty associated to steam condensation must be high as it is impossible to confirm their flowrates through measurements unless all of them are connected to a condensate return system.

**Case 17 - Steam leaks** Three methods exist to estimate the flowrate of steam through a leak:

1. The plume length of a leak can be measured to estimate the flowrate of lost steam [43].
2. The leak diameter can be measured and based on pressure difference calculations, the flowrate can be estimated. Leaks are rarely circular making this method complicated.
3. As steam leaks are generally numerous, obtaining such information can be very laborious. It is therefore recommended to perform an extensive survey and calculate mean flowrate of leaks per pressure level. Estimates can be made based on the total amount of steam leaks and their pressure levels, though an important number of man hours may be required to identify each leak, especially in large sites. These values should be updated regularly.
   Once the mean steam leak flowrates $\bar{m}_{leak_j}$ are established for each site's pressure level $j$ and the total number of leaks $n_{leak,h_j}$ per header $h_j$ has been counted or estimated, the flowrate from leaks for each of the headers can be estimated using equation 3.11.

$$m_{leak,h_j} = n_{leak,h_j} \times \bar{m}_{leak_j} \tag{3.11}$$

Similarly to condensate losses, high uncertainty values must be used as the methods are very approximative.

## 3.4 Application to the Typical Industrial Cluster

The steam networks were modelled in the Belsim Vali® Data Reconciliation and flowsheeting software [52]. The flowchart in Figure 2.2 describes the extent of the modelled interconnections. Table 3.2 presents the number of measured thermodynamic states associated to Figure 2.2 (145 in total). The PUs were not included in the Data Reconciliation of this case study.

The properties were defined as input (measured values or assumptions to be reconciled $\mathbf{y}$) and unknowns (those to be calculated by the model $\mathbf{x}$). Flowrates make up the majority of the measures and unknowns using the modelling rules defined in Section 3.3.2.

Flowrate boundaries were applied to turbines and boilers using information described in Tables 2.1 to 2.3. In this way, the Data Reconciliation was prevented from modifying values beyond their possible states. High pass, low pass and cutoff filters were applied to all measurements to correct gross errors using the parameters proposed in Table 3.1.

The Data Reconciliation was carried out for the 365 days of the TIC's data and provided generally good results. The key findings of the application are presented below, as well as the reconciled steam demand in Sections 3.4.8 to 3.4.10. These results can also be found online at [53].

Table 3.2 – Number of thermodyamic properties defined in the data reconciliation of the Typical Industrial Cluster.

| | | Site R | Site P | CB |
|---|---|---|---|---|
| Flowrates | Input | 28 | 31 | 3 |
| | Unknown | 8 | 18 | 0 |
| | Total | 36 | 49 | 3 |
| Pressures | Input | 11 | 13 | 3 |
| | Unknown | 8 | 8 | 0 |
| | Total | 19 | 21 | 3 |
| Temperatures | Input | 8 | 8 | 3 |
| | Unknown | 7 | 12 | 0 |
| | Total | 15 | 20 | 3 |
| Power | Input | 0 | 0 | 0 |
| | Unknown | 3 | 4 | 0 |
| | Total | 3 | 4 | 0 |
| Turbine $\eta$ | Input | 3 | 4 | 0 |
| | Unknown | 0 | 0 | 0 |
| | Total | 3 | 4 | 0 |
| Losses data | Input | 4 | 4 | 0 |
| | Unknown | 0 | 0 | 0 |
| | Total | 4 | 4 | 0 |

Two reconciliation examples are shown in Sections 3.4.1 and 3.4.2 respectively showing the effects of random and systematic errors. This is followed by an analysis of the Penalty described in equation 3.1, the losses and flowrates of turbines and letdowns. The overall results of the TIC demand are presented in Sections 3.4.8 to 3.4.10.

### 3.4.1 Example of reconciliation 1 - Random error

Figure 3.8 shows typical reconciliation results for a flowrate measure in (a) and zoomed between days 120 and 150 in (b). The example of Site R's 20 barg Utility (U) consumption is used. The graph depicts the following:

- Shaded blue area: Uncertainty, set at 8% of the measured value. Mean value: $\pm$ 2.5 t/h.
- Blue line: Measured value of flowrate, mean: 31.8 t/h.
- Red line: Reconciled value of flowrate, mean: 31.1 t/h.
- Black line: Difference between reconciled and measured value, mean: -0.7 t/h with a peak at -5.7 t/h.

Graph (a) and (b) clearly show that the trend of the measured value is well followed by the reconciled value. The difference varies between -6.3 t/h and 1.1 t/h and is generally below zero. The largest differences occurring when the measured flowrate is itself high. The mean difference between the reconciled and measured value is equal to -2% of the mean measure.

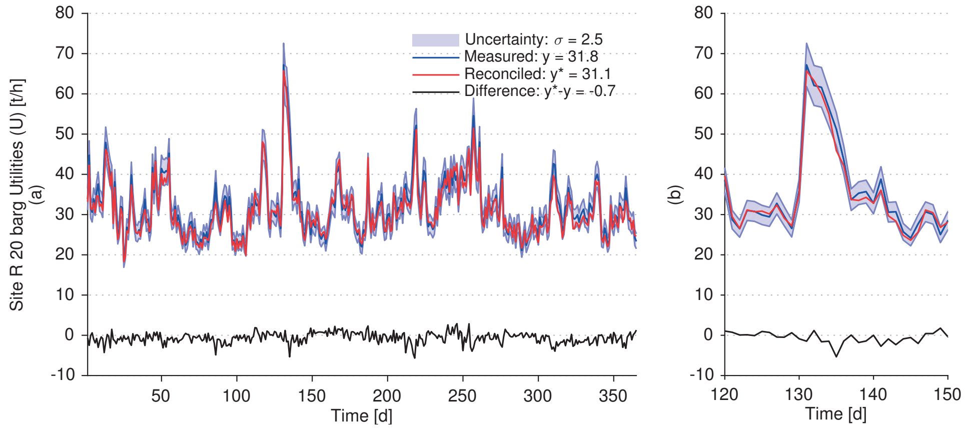



Figure 3.8 – Reconciliation of Site R's Utilities (U). Yearly data in (a), zoomed in (b). Mean values shown in the legend.

While it is not possible to conclude that the reconciliation is correct, expanding this analysis to other measures builds trust in the obtained results.

### 3.4.2 Example of reconciliation 2 - Systematic error

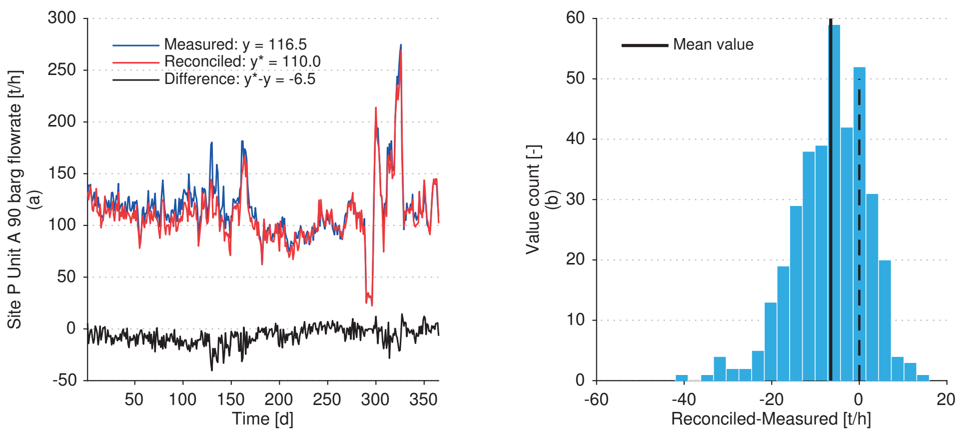



Figure 3.9 – Reconciliation of Site P PU A 90 barg steam consumption (a) and a histogram of the difference (b).

The reconciled 90 barg steam flowrate of PU A can be seen in Figure 3.9, which shows the measured versus reconciled values of consumption through time in (a) and a histogram of the difference between the two in (b). The mean difference between the reconciled and measured flowrate is -6.5 t/h seen in black on the histogram, with a peak of -40.3 t/h. 76.2% of the values are negative, which can be explained by a sensor calibration issue.

### 3.4.3 Penalty

The Penalty described in Equation 3.1 is a measure of the amount of correction taking place in a model. Its values are shown for each time step in Figure 3.10 (a) with its histogram in (b).

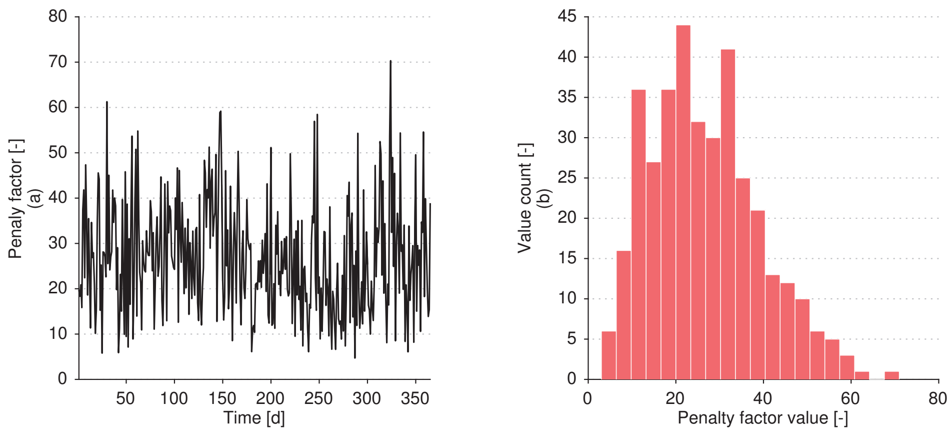



Figure 3.10 – Penalty of Data Reconciliation model through time in (a) with its histogram in (b).

The Penalty is unique to every model and data set and is best interpreted relatively. Its mean value for the model over the 365 day period is 26.7 and reaches a maximum of 70.3 on day 324. The histogram shows that 82% of values are regrouped between 10 and 40. High penalty values (for example above 40) should be investigated as they may result from bad modelling or gross measurement errors.

The highest penalty occured as a result of pressure reading reconciliation on the 5 barg pressure network of Site R. The pressure of the outlet of Site R's 20 barg letdown (before superheating) was reconciled at 5.3 barg rather than its 3.9 barg measured value. This in itself created 42% of the Penalty. The measure is very likely to be erroneous as the lower pressure header is typically at 5.2 barg.

### 3.4.4 Losses

**Site R** Figure 3.11 shows an analysis of the steam leaks (a & c) and condensation losses (b & d) for Site R. For both pressure levels, steam leaks estimates were heavily modified while condensation losses were not.

The 20 barg steam leak flowrate has a mean value of 5.4 t/h compared to the estimated mean 6.3 t/h, with important variations in the reconciliation. The mean reconciled condensate value was 2.0 t/h, as its design value of 2.0 t/h. This makes a mean 20 barg steam loss of 7.4 t/h, with a peak value of 14.3 t/h.

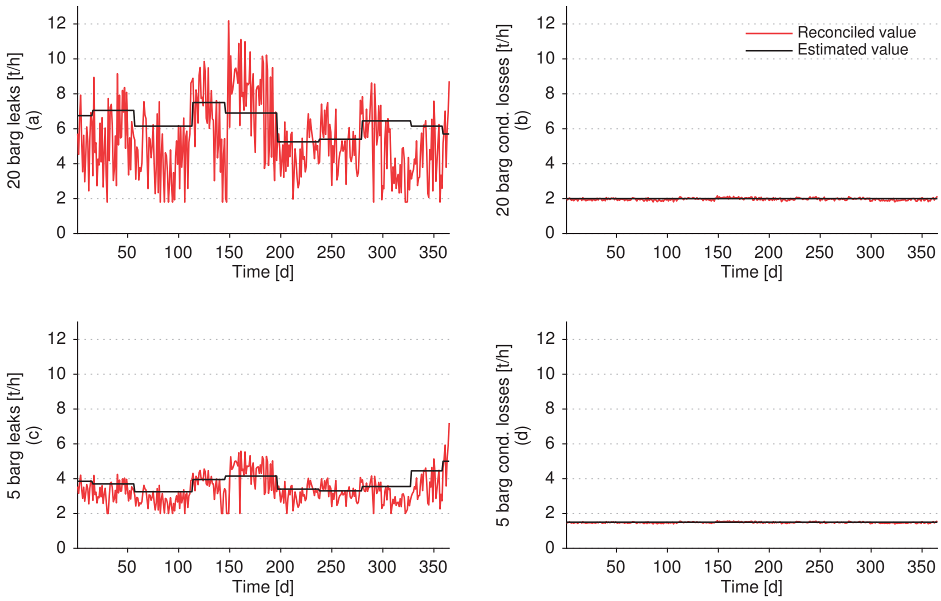



Figure 3.11 – Site R steam leaks (a & c) and condensation losses (b & d) for the 20 barg and 5 barg headers.

The 5 barg steam leaks had a mean value of 3.4 t/h compared to the estimated mean 3.7 t/h, also with heavy important variations. The mean reconciled condensate value was 1.5 t/h, equal to its design value. This makes a mean 5 barg steam loss of 4.9 t/h, with a peak value of 8.8 t/h.

The most logical explanation for these findings is that more correction takes place on the leaks than condensation because the uncertainty of the value is set higher ($\sigma = 50\%$ for leaks, $\sigma = 30\%$ for condensates).

While the time series data show important differences between the estimated and reconciled leaks, their mean values do not differ significantly, which could have been expected given the amount of uncertainty associated to the values.

For this work the leak size was set as a constant, though it could also be associated to an uncertainty factor to improve the model. However, given the already large uncertainty on the leaks, the effects of such an action could overcomplicate the reconciliation and probably lead to convergence errors.

The reconciliation suggest that a mean value of 12.2 t/h steam is lost, with a peak of 20.4 t/h.

**Site P** Figure 3.12 shows an analysis of the steam leaks (a & c) and condensation losses (b & d) for Site P.

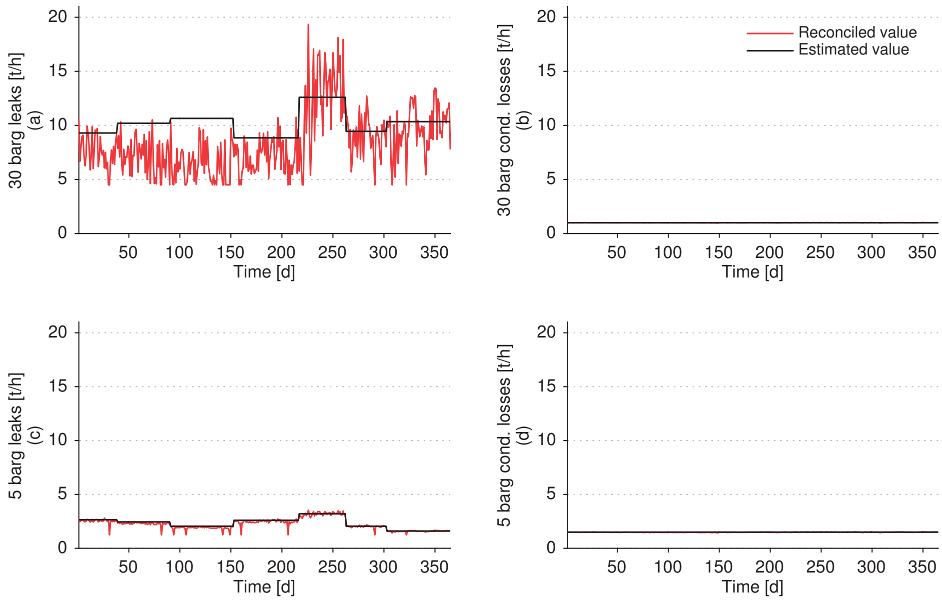



Figure 3.12 – Site P steam leaks (a & c) and condensation losses (b & d) for the 30 barg and 5 barg headers.

The 30 barg steam leak flowrate has a mean value of 10.0 t/h compared to the estimated mean 12.2 t/h, with important corrections. The mean reconciled condensate value was 1.0 t/h, equal to its design value. This makes a mean 20 barg steam loss of 11.0 t/h, with a peak value of 24.2 t/h.

The 5 barg steam leaks had a mean value of 2.2 t/h compared to the estimated mean 2.3 t/h, following the trend very closely. The mean reconciled condensate value was 1.5 t/h, equal to its design value. This makes a mean 5 barg steam loss of 3.7 t/h, with a peak value of 5.1 t/h.

With the proposed methods for calculating the steam leak and condensation flowrates, the reconciliation suggest that a mean value of 14.8 t/h steam is lost, with a peak of 29.3 t/h. The closeness of fit between the reconciled and measured leak values for the 5 barg header can either be seen as a confirmation of the method, or as an opening for further investigation to better understand the influence of the uncertainties.

### 3.4.5 Turbines

As the mechanical power production was not made available in the original data set, its calculation results from the Data Reconciliation model. This was made possible as the design isentropic efficiency of the turbines is known (Table 2.1). Figure 3.13 shows the turbine power versus flowrate for Site R and P while Table 3.3 shows the mean and maximum flowrates through the turbines as well as the power production and specific power.

Table 3.3 – Flowrates and power of Site R and P turbines.

| | Turbine flowrate [t/h] | | Turbine Power [kW] | | Specific power [kWh/t] | |
|---|---|---|---|---|---|---|
| | Mean | Max | Mean | Max | Mean | Max |
| RT1 | 84.4 | 87.8 | 6992.5 | 7681.1 | 82.9 | 87.5 |
| RT2 | 36.6 | 84.5 | 3004.7 | 6991.4 | 82.0 | 85.3 |
| PT1 | 45.9 | 50.4 | 4900.1 | 5567.0 | 106.8 | 111.3 |
| PT2 | 104.1 | 114.0 | 5938.0 | 6688.8 | 57.0 | 59.8 |
| PT3 | 0.8 | 28.6 | 23.1 | 898.4 | 30.4 | 31.8 |

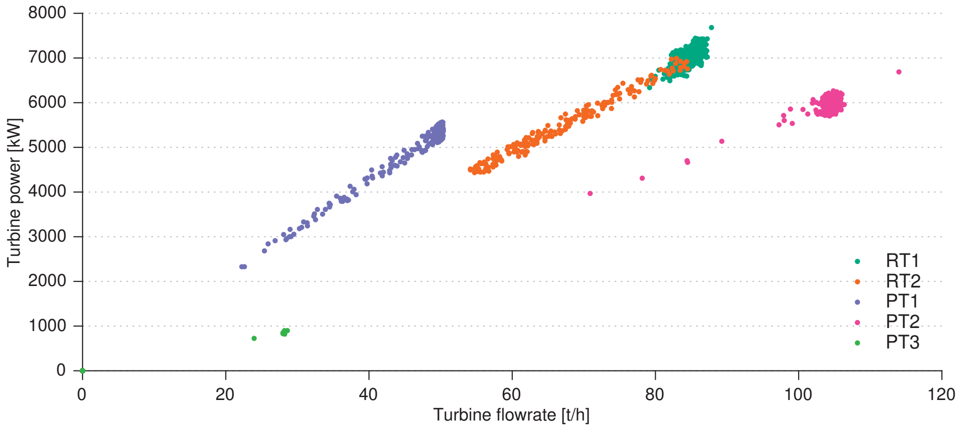



Figure 3.13 – Scatter plot of power versus flowrates of turbines for Sites R and P.

The specific power varies with time as the temperature and pressure conditions change, though a clear trend can be observed. The differences remain relatively small in comparison to the mean value.

### 3.4.6 Letdowns and desuperheating

Table 3.4 – Letdown flowrate and desuperheating values calculated by model.

| | Inlet [t/h] | | Desuperheating [t/h] | |
|---|---|---|---|---|
| | Mean | Max | Mean | Max |
| RL1 | 41.7 | 98.6 | 6.3 | 15.2 |
| RL2 | 18.4 | 42.5 | 1.6 | 4.4 |
| PL1 | 19.1 | 92.1 | 1.6 | 6.7 |
| PL2 | 54.9 | 194.8 | 9.1 | 33.8 |

Table 3.4 shows the mean and maximum calculated letdown flowrate values resulting from the Data Reconciliation. The first two columns refer to the inlet flow of the letdowns while the remaining detail the amount of demineralised water injected into the letdown steam. The demineralised water flow which can also be seen in Figure 3.14 as a percentage of total steam flow.

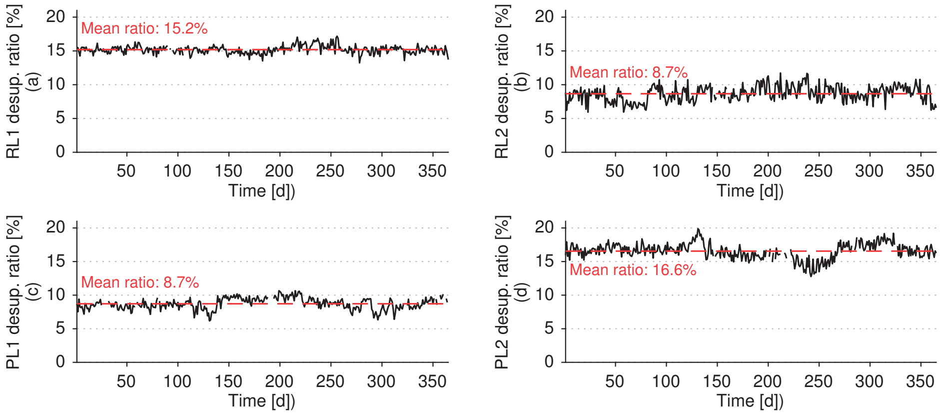



Figure 3.14 – Calculated desuperheating ratio for Site R (a & b) and P (c & d) letdowns.

The demineralised water flows remain quite stable with the most significant variations in the PL2 letdown (30 barg to 5 barg of Site P). Variations in desuperheating ratio were to be expected as temperatures within steam headers depend on PU production as well as activation of turbines and letdowns.

### 3.4.7 Sources of error and innacuracy

While it is not possible to say that a reconciliation is correct, thanks to an analysis, these results can be considered satisfactory. Several sources of errors and innacuracies are still present and could be eliminated through future work:

- **Large site utility consumptions:** Both sites are plagued by very large steam consumption for the site utilities with only bundled steam flow measures available. More detailed modelling of these demands would potentially allow the identification of further steam leaks, condensation losses and perhaps even wasted steam.
- **Modelling of PUs:** PUs were not modelled at all in this work, though their details can be found in Appendix A. Modelling of the internal PU steam consumption/production would have been very useful for reconciling their steam imports and exports. Furthermore it would lead to a greater understanding of the PU steam uses, losses, cooling, and unknown consumers.
- **Thermal losses:** Due to a lack of temperature measurements, thermal losses were not modelled at all. This means that no relation can be established between them and the condensation losses, though one might exist. Obtaining such values would allow the financial quantification of the thermal losses and would justify maintenance missions.
- **Pressure losses:** Due to a lack of pressure measurements, no pressure losses were considered across the headers. The consequence is that any further thermodynamic analysis may overestimate the steam pressure within pipes. Reductions in steam pressure lead to reduced steam saturation temperatures which can have important consequences when sizing heat exchangers, especially those with small approach temperatures.

### 3.4.8 Site R steam demand

Table 3.5 shows the reconciled mean and maximum steam consumption for Site R over a representative year. Negative values indicate a net export of steam from the PU. The value in brackets corresponds to the difference between the reconciled and measured value.

Table 3.5 – Reconciled steam demand for Site R (reconciled-measured).
Mean demand: 164.9 t/h.

| | 90 barg [t/h] | | 20 barg [t/h] | | 5 barg [t/h] | |
|---|---|---|---|---|---|---|
| | Mean | Max | Mean | Max | Mean | Max |
| Unit A | | | 10.8 (-0.1) | 20.2 (0.4) | -4.1 (-0.0) | -10.4 (-0.0) |
| Unit B | | | 10.2 (-0.1) | 16.5 (-0.0) | | |
| Unit C | 13.4 (-0.1) | 22.7 (-0.6) | 8.9 (-0.1) | 19.3 (0.0) | -12.9 (-0.1) | -28.3 (-1.1) |
| Unit D | -12.8 (-0.2) | -20.4 (-0.4) | 7.5 (-0.1) | 18.0 (-0.4) | 8.2 (-0.0) | 18.6 (-0.0) |
| Unit E | | | 19.7 (-0.3) | 27.7 (-0.7) | 13.4 (-0.1) | 19.5 (0.5) |
| Unit F | | | 15.8 (-0.2) | 27.3 (-0.8) | | |
| Utilities (U) | | | 31.1 (-0.7) | 65.7 (-1.5) | 25.8 (-0.4) | 33.1 (0.0) |
| Utilities (U1) | | | 6.1 (-0.0) | 22.5 (-0.2) | 11.6 (0.0) | 26.8 (0.2) |
| Utilities (UT) | | | 26.8 (-0.0) | 48.3 (0.2) | -26.8 (0.0) | -48.3 (-0.2) |
| Atmosphere | | | | | 0.1 (0.0) | 21.2 (1.3) |
| Losses | | | 7.4 (7.4) | 14.3 (14.3) | 4.9 (4.9) | 8.8 (8.8) |
| Total | 0.6 (-0.3) | 19.8 (-1.3) | 144.3 (5.8) | 184.7 (4.5) | 20.0 (4.2) | 45.9 (2.4) |
| Boiler 1 | 71.1 (0.7) | 92.2 (1.4) | | | | |
| Boiler 2 | 80.1 (0.7) | 93.0 (2.2) | | | | |
| CB | 5.8 (0.0) | 52.4 (-1.1) | | | | |
| Desup. water | | | 6.3 (6.3) | 15.2 (15.2) | 1.6 (1.6) | 4.4 (4.4) |

In general, the difference between reconciled and measured values is small and well within expected accuracies of orifice plate flowmeters. The largest differences come from the losses and demineralised water injected into the steam in the desuperheaters, as neither of them are measured.

### 3.4.9 Site P steam demand

Table 3.6 shows the mean and maximum steam consumption for Site P over a representative year. Negative values indicate a net export of steam from the PU.

As analysed above, PU A's 90 barg is the most heavily penalised PU, with a -5% correction on average. Its peak 5 barg production is also heavily modified, increasing from 148.9 t/h to 172.0 t/h. These results are not surpising as PU A is the largest consumer and producer of steam in Site R. As the $\sigma$ values are relative rather than absolute, large flowrates are more likely to have higher reconciliation.

Table 3.6 – Reconciled steam demand for Site P (reconciled-measured).
Mean demand: 325.6 t/h

| | 90 barg [t/h] | | 30 barg [t/h] | | 5 barg [t/h] | |
|---|---|---|---|---|---|---|
| | Mean | Max | Mean | Max | Mean | Max |
| Unit A | 110.0 (-6.5) | 269.4 (-5.4) | -57.0 (-1.3) | -126.5 (8.4) | -39.5 (-0.9) | -172.0 (-23.1) |
| Unit B | | | 32.1 (-0.4) | 70.0 (0.2) | 9.3 (-0.0) | 17.7 (-0.2) |
| Unit C | | | 60.5 (-1.6) | 93.3 (-0.4) | 12.8 (-0.1) | 21.8 (0.0) |
| Unit D | | | 7.9 (-0.0) | 13.2 (0.0) | | |
| Unit E | | | 45.3 (-0.9) | 68.4 (-1.2) | -29.7 (-0.4) | -54.0 (-1.5) |
| Unit F | | | 18.0 (-0.1) | 24.8 (0.1) | 27.2 (-0.3) | 34.9 (-0.4) |
| Utilities (U) | | | 22.1 (-0.2) | 65.6 (0.3) | 57.2 (-1.4) | 93.7 (-1.9) |
| Utilities (U1) | | | 0.9 (-0.0) | 8.9 (0.0) | 14.3 (-0.1) | 21.7 (0.0) |
| Utilities (U2) | | | 3.6 (-0.0) | 14.2 (-0.0) | 13.7 (-0.1) | 21.9 (-0.1) |
| Utilities (UT) | | | 4.7 (-0.0) | 5.5 (-0.0) | -4.7 (0.0) | -5.5 (0.0) |
| Atmosphere | | | | | 1.4 (-0.1) | 66.5 (-5.3) |
| Cond. turbine | | | | | 0.8 (-0.0) | 28.6 (-0.4) |
| Losses | | | 11.0 (11.0) | 24.2 (24.2) | 3.7 (3.7) | 5.1 (5.1) |
| Total | 110.0 (-6.5) | 269.4 (-5.4) | 149.0 (6.5) | 258.2 (13.6) | 66.6 (0.5) | 148.0 (-0.2) |
| Boiler 1 | 123.6 (1.1) | 131.7 (2.6) | | | | |
| Boiler 2 | 126.2 (1.2) | 135.0 (4.2) | | | | |
| Boiler 3 | 53.0 (0.1) | 123.4 (-0.7) | | | | |
| CB | 12.2 (0.0) | 97.7 (-1.2) | | | | |
| Desup. water | | | 9.1 (9.1) | 33.8 (33.8) | 1.6 (1.6) | 6.7 (6.7) |

### 3.4.10 Overall steam demand

Figure 3.15 shows the overall steam demand for the TIC in graph (a) and the load duration curves in graph (b). Table 3.7 shows the key properties of the TIC's steam demand.

Table 3.7 – Reconciled total steam demand overview

| | Installed | All levels [t/h] | | 90 barg [t/h] | | 20/30 barg [t/h] | | 5 barg [t/h] | |
|---|---|---|---|---|---|---|---|---|---|
| | | Mean | Max | Mean | Max | Mean | Max | Mean | Max |
| Site R | 180 | 164.9 | 213.5 | 0.6 | 19.8 | 144.3 | 184.7 | 20.0 | 45.9 |
| Site P | 390 | 325.6 | 467.9 | 110.0 | 269.4 | 149.0 | 258.2 | 66.6 | 148.0 |
| CB | 260 | | | | | | | | |
| Total | 830 | 490.5 | 662.4 | 110.6 | 266.5 | 293.3 | 434.5 | 86.6 | 169.1 |

The mean overall demand is 490.5 t/h with a peak value of 662.4 t/h on day 243. This is a shift from the measured data, which recorded a peak demand of 624.9 t/h on day 312. It can be explained by the existence of previously uncalculated losses, which make up 39.2 t/h on day 243 compared to their average 27.0 t/h. The calculations of the desuperheated steam also contributed towards these numbers, permitting for the mass balances of the steam network to be closed.

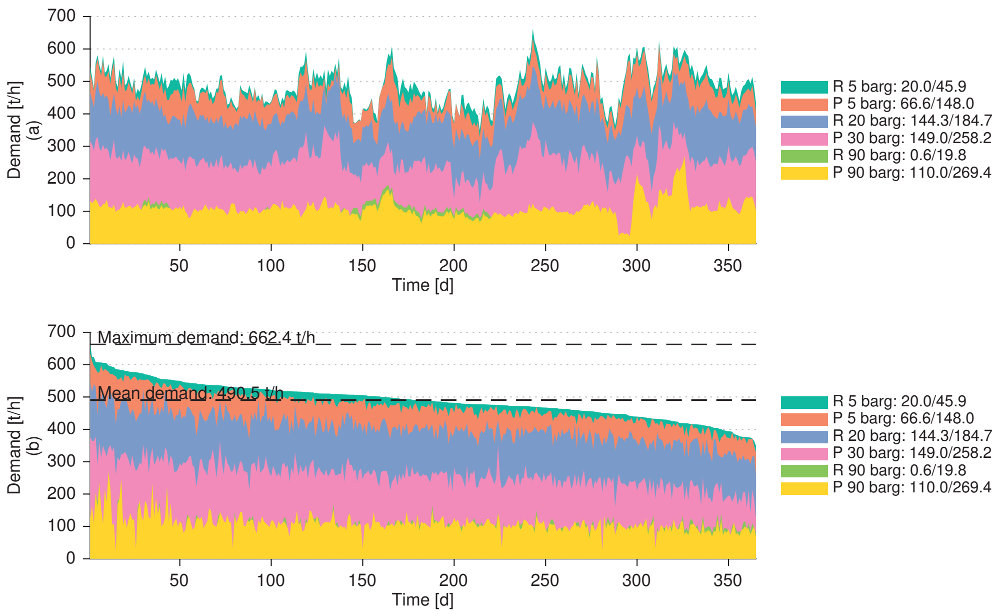



Figure 3.15 – Reconciled steam demand overview for the Cluster

## 3.5 Conclusion

Every industrial metering system is subject to errors be they random or systematic. Gross errors are also inevitable, though these can be addressed through maintenance.

Industrial sites are also unable to measure every possible thermodynamic state, for financial as well as technical reasons. For example, space for a flowmeter may not be available, just as steam leaks cannot be measured conventionally.

In the case of the refining and petrochemical industry, the combination of inaccurate measurements and unmeasured thermodynamic states leads to open mass and energy balances, which must be closed for high accuracy energy efficiency studies to be carried out.

Data Reconciliation is a time tested tool for dealing with such problems as it improve the accuracy of measures and estimations. When combined to flowsheeting software, it can also be very helpful for accurately calculating unknown thermodynamic states.

This chapter has not proposed developments towards the Data Reconciliation theory, but has rather established what are the key data issues faced by the refining and petrochemical industry as well as a methodology to help in data collection, filtering and modelling of their steam networks in view of Data Reconciliation. In this way 17 types of typical steam flows were detailed.

The proposed methodology was applied to the Typical Industrial Cluster case study data. The steam networks of the Site's R and P were modelled, using a total of 145 thermodynamic properties which were then reconciled. By estimating steam losses based on industrial data and calculating other unknowns such as letdown flows, this permitted for the mass and energy balances of the TIC to be closed.

Through the closed mass and energy balances of the system it is now possible to carry out energy efficiency studies with higher confidence in the data and therefore the generated results.

The peak demand of the TIC, a key property for sizing any investments, was established to be 662.4 t/h rather than the previously calculated 624.9 t/h. Furthermore, calculations of the steam losses permits a better management of future loss reduction projects.

An added benefit of the reconciliation of the entire cluster could also be improved accounting of the steam, an important consideration if symbiosis projects between Site R and P are to be established.

This work could have benefited from more advanced methods such as dynamic Data Reconciliation or advanced recycling of previously identified results. This would permit more accurate and dependable reconciliation, verified through time.

# 4 Identification of representative periods

*This chapter presents a computer aided methodology to identify representative scenarios in large data sets.*

> Then there is the man who drowned crossing a stream with an average depth of six inches.
>
> *W.I.E. Gates*

## 4.1 Introduction

Modern industrial data systems offer possibilities to measure and monitor process equipments to a very high degree of accuracy. As the sampling of sensors takes place at a high frequency, the resolution and amount of data available can be significant.

Operators make use of this data to control their systems and safely manage their production output. Engineers may use this data to better understand the systems leading to the elaboration of accurate improvement opportunities.

For engineers, past data is typically used to represent expected future operations. However, in order to be workable and presentable, the resolution of the data must be adapted to the type of study. Engineers therefore have the task of condensing this high quantity of data while preserving its key properties, for example its variations.

Some causes for variations in thermodynamic properties of industrial sites are presented in Section 4.1.1. This is followed by a discussion on the risks associated with using mean values of data in Section 4.1.2 and the need for scenario based approaches for engineering studies in 4.1.3.

A methodology to identify representative operating periods of industrial sites within large data sets is presented in Section 4.3 as well as its application to the Typical Industrial Cluster in 4.4.

### 4.1.1 Variation in cluster utility demand

While a Process Unit (PU) may have relatively predictable operational regimes, industrial sites and clusters as a whole are subject to much more variation. These may strongly impact the utility network demand. Some explanations behind these variations are:

- PU shutdown: In a industrial cluster with multiple PUs, it is unlikely that all of them will be producing at the same time [40]. Planned turnarounds, feedstock availability or economic factors can lead to increased or reduced production rates. When these PUs go through shutdowns or slowdowns, their steam consumption collapses, as does their steam generation.
- PU demand variation: The assumption that PUs have stable utility demand is false in the refining and petrochemical industry [34], as the demand can vary significantly based on which of its sub-units are activated, which feedstock is used and the PU throughput. Several examples are given below:
  - Turbo-pump/compressor activation: Steam turbines used to power compressors, pumps and aerofans are often backed up by motorised counterparts for redundancy. Cycling between the motorised and steam powered devices will lead to variations in the demand of steam.
  - Heat exchanger fouling: Fouling occurs as a result of deposition of process material in heat exchangers, leading to reduced energy recovery and increased pressure drop [49], and thus potentially higher energy demand. This phenomenon is common in refineries where material streams may contain important amounts of impurities.
  - Ageing catalysts: As catalysts age, their selectivity decreases leading to reduced conversion efficiency and increased heat production [50]. As this heat is often evacuated through steam generation, ageing catalysts may in fact produce more steam, thus reducing overall demand.
- Utility demand variation: The consumption of steam by the utilities of an industrial site vary depending on meteorological conditions, feedstocks and products amongst others. For example, the steam consumption of water demineralisation complexes is linked to overall steam demand. High steam demand means higher demineralised water demand and therefore more steam must be injected into degassers to prepare the water. Similarly, tank tracing will depend on the quantity and quality of the tank contents.
- Extreme events: Extreme weather events such as storms and flooding may have the effect of increasing steam consumption as condensation increases in pipes. Electricity networks can also be taken offline as a result of lightning strikes. Equipment failures are never planned and can lead to increased or decreased steam consumption.

The variation of PU utility demand can strongly affect the operability of the solutions stemming from engineering studies. For example, if steam generated by a PU is no longer available when it goes offline, steam boilers may have to generate more steam. If a network is poorly sized, a combination of such events can lead to an undersupply of steam as operating reserves fall to zero.

To guarantee the operability of a network through time, investment solutions must be shown to operate in the expected configurations of the industrial site. Given the high sampling frequency of measurement devices, it is computationally infeasible to carry out studies on each possible configuration or time step of a cluster. Averaged data sets are therefore used to reduce the amount of data being handled.

### 4.1.2 The problem with averages

Engineering studies can use yearly or monthly timespans to define periods over which mean thermodynamic states can be calculated. The dangers of such gross averages are that they fail to capture properties such as the maximum demand of the site or PU shutdown. This problem is also referred to as the *tyranny of averages* in the field of statistics [51].

An example is given in Figure 4.1, in which the steam consumption profile of a PU is shown in black. Two periods of PU shutdown can be seen around day 150 and 275. The design value of steam flowrate can be seen in green and the mean flowrate in red. Mean monthly values are shown in blue.

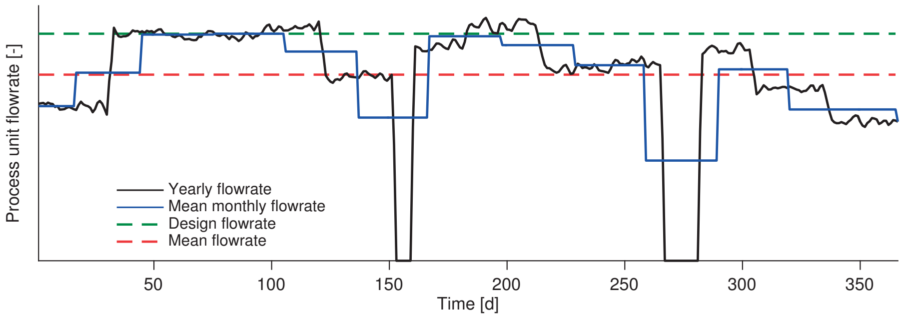



Figure 4.1 – Example of PU steam flowrate.

The figure shows that the steam consumption is rarely equal to the design value. Similarly, the mean yearly value is rarely representative of the flowrate, and logically lies between the maximum and minimum values. Monthly means are as often on target as off target, failing to capture variations and even leading to totally erroneous minimum demand values. The monthly mean value in the second PU shutdown (around day 275) corresponds to no operational reality and is potentially misleading.

While a PU may have a certain design consumption, its value will depend on the many factors mentioned above. As such, it should not be the unique value used to represent the PU's flowrate.

### 4.1.3 Scenario based approaches

To overcome the limitations of gross averages, scenario based studies allow engineers to quantify the impacts of future operations on based on an analysis of key variables, such as system costs and efficiency [69] of representative fields. These key variables can be identified through system analysis and prior knowledge.

Scenario building can be complex as they must be communicative, pertinent, coherent, relevant and transparent [70]. Furthermore, they can be exploratory (based on previous trends) or normative (providing alternative images of the future). Given the uncertainty of the future, building quality scenarios often relies on process knowledge.

Process knowledge can be used to establish the most significant operational modes of a PU and to forecast future changes to equipments or feedstocks. However, certain operational modes which are not recognised as strategically important may be omitted through scenarios defined by engineers. In this way transparency is not achieved.

A set of scenarios should ideally capture all the operational modes of a PU, to ensure that a maximum of information is used [69]. Entire data sets may therefore be analysed in order to identify the typical and exceptional operating modes. However, when dealing with multiple PUs, building scenarios based on process knowledge and data analysis becomes increasingly difficult, as PUs behave independently from one another anddata quantities may be overwhelming.

### 4.1.4 Objectives

For these reasons, a computer aided method is required to identify representative periods, common to multiple profiles, from which representative operational scenarios can be identified.

Such a method is proposed in this Chapter, based on the work by Bungener et al. [40]. It identifies representative operating periods of an industrial cluster made up of several PUs, exploiting a multi-objective optimisation to identify $p$ periods that delimit typical operating modes of multiple profiles.

## 4.2 State-of-the-art

Process Integration studies have often based themselves on mean values [55] to calculate energy efficiency improvements. The Time Slice approach [57] was developed to address process integration of batch processes and to include thermal storage. In batch processes it is relatively simple to define operational scenarios as operations of sub-units follow strict orders in their operations.

Other studies have introduced mathematical formulations to address multi-period problems in Pinch Analysis [63], typically using operational scenarios, though none have addressed how to optimally identify the periods.

A non-linear optimisation to identify recurring loads [65] was limited by the fact that they were not translated into common periods for multiple profiles.

In district heating problems, traditional methods include using monthly means, though discretisation and parametrisation of load duration curves has also been introduced [60]. This leads to non sequential periods. In district heating problems it is important to identify seasonal and daily operations, reason for which the concept of Typical Days was introduced. Here, the $k - means$ algorithm [66] was used to identify $k$ 24 hour representative periods [61]. These can also be transformed into sequential periods [62] while considering heating demand and electricity demand profiles simultaneously.

The methods applied in district heating problems cannot be transferred to the process industry as intra-day variation is less of a concern and multiple profiles must be considered simultaneously.

None of the mentioned innovations address the periods in which PUs may shutdown. These shutdowns can have important consequences on system sizing as demonstrated in [40]. The paper showed that engineering studies based on yearly means lead to systems being undersized with respect to maximum demand, which take place when steam generating PUs go offline. These periods of zero flowrates must be incorporated into scenario based studies.

The above analysis has shown that a method is needed to identify representative periods common to multiple profiles which respect periods of PU shutdowns and zero flowrates. An example is given in Figure 4.2, showing two profiles (P1 & P2) spanning 30 days. The profiles are cut into 7 periods, from which scenarios can be extracted.

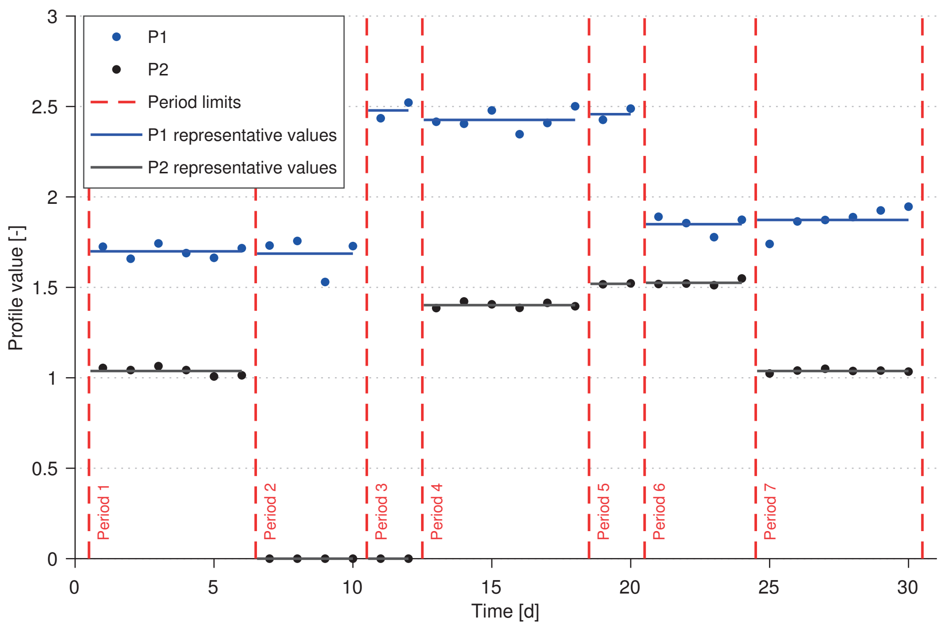



Figure 4.2 – Example of scenario identification.

1. The red lines delimit 7 periods. The first period lasts from day 1 to 5, the second from day 6 to 9 and so on.

2. The blue and black lines identify representative values during the chosen periods. These are a good fit with the original data.

3. Between days 7 and 12, Profile 2 is equal to zero, which is respected through the identified periods.

A method to achieve such aims would meet several of the criteria for quality scenario building. As no data would be omitted, they would be transparent and communicative, though still lacking in normative properties. Given the large number of variations in energy demand in refining and petrochemical clusters, it is assumed that such a method would aptly represent possible future variations, though the effects of strongly increasing energy demand as a result of new PU investments would not be covered or decomissioning without future sensitivity analysis.

## 4.3 Methodology

This section presents the methodology to identify representative periods of operations within large data sets. Rather than use all available data, key drivers of variation should be used, for example PU feedstock flowrate and steam demand. A certain amount of process knowledge is required to best choose these data as well as their importance.

The proposed algorithm identifies representative periods over multiple profiles, with the following properties:

1. Periods common to all profiles: The method identifies $p$ periods between the start and end of the data set. An index of periods $\mathbf{I}$ delimits these periods, common to all profiles. $p$ is chosen by the experimenter.

2. Closeness of fit: A good fit is sought between original profiles and the scenarios obtained from the period index. The standard deviation between the identified period and the original data is minimised. A performance indicator ($\sigma$) representing the standard deviation between the representative periods and all the original profiles is used. Profiles can be normalised so as to confer their importance.

3. Respect of zero flowrate periods: Zero flowrate periods typically occur when PUs shutdown. They are important when dealing with large industrial sites, as they represent periods when utility demand or supply may not be present. A performance indicator is defined ($\Delta$), which counts the number of zero flowrate time steps which are not respected. This indicator is minimised.

### 4.3.1 Algorithm

The algorithm exploits an Evolutionary Multi-Objective Optimisation (EMOO) [74] to search for the best index of periods which minimises the performance indicators $\sigma$ and $\Delta$ as represented in Figure 4.3 and detailed step by step below:

1. Prepare data: Identify zero flow periods, normalise and apply weights ($\omega$) to data.
2. Initialise $u$ random vectors $\mathbf{x}$.
3. Construct indexes $\mathbf{I}$ from the $\mathbf{x}$ vectors. The indexes $\mathbf{I}$ are made up of $p$ periods.
4. Evaluate the indexes according to $\sigma(\mathbf{I})$ and $\Delta(\mathbf{I})$.
5. Apply evolutionary mechanisms to the best performing indexes, eliminate others.
6. Repeat steps 3 and 4 until $v$ indexes are evaluated.
7. Analyse results and choose appropriate index.

The performance indicator $\sigma$ identifies the goodness of fit between the initial data and that resulting from the identified periods, and the $\Delta$ indicator counts the number of zero flowrate periods which are not respected. These are detailed below.

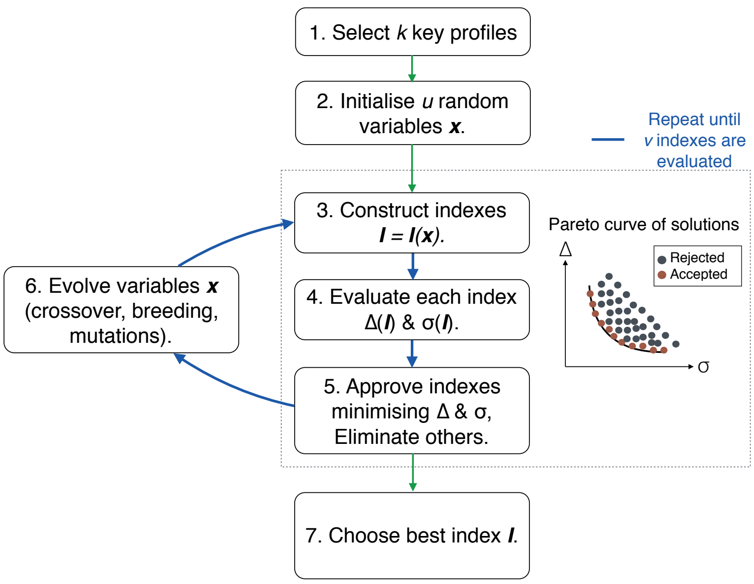



Figure 4.3 – Flowchart of representative period identification.

#### Step 1 - Data preparation

Once a choice has been made on which $k$ profiles $p_i$ are to be used in the algorithm (which can include thermodynamic states of flows, weather variations or even economic profiles), their values can be normalised, as seen in Equation 4.1, creating $k$ profiles $q_i$. The interest of normalisation is to give each profile a particular weight $\omega_i$. Profiles with higher weights will have higher influence on the performance indicators.

$$q_{i,t} = \frac{\omega_i \cdot p_{i,t}}{\sum_{i=1}^{T} \frac{p_{i,t}}{T}} \quad t \in [1, \ldots, T] \quad i \in [1, \ldots, k] \tag{4.1}$$

### Step 2/3 - Index initialisation and construction

Each index of periods $\mathbf{I}$ is associated to a vector $\mathbf{x}$ from which it is constructed, $\mathbf{x}$ is the variable of the EOO. $\mathbf{x}$ is a vector of random values shown in Equation 4.2. This vector is cumulatively summed to create a vector of length equal to the sum of the values, which will then be normalised with respect to the total time $T$, as seen in Equation 4.3 to create $\mathbf{I}$.

$$\mathbf{x} = [x_1, x_2, \ldots, x_{n+1}] \quad x_i \in [0, 1] \forall i \tag{4.2}$$

$$\mathbf{I} = \frac{T}{\sum_{j=1}^{n+1} x_j} \cdot [x_1, \sum_{j=1}^{2} x_j, \sum_{j=1}^{3} x_j, \ldots, \sum_{j=1}^{n+1} x_j] \tag{4.3}$$

The resulting index of periods $\mathbf{I}$ is a vector of $n+1$ sequential values between 1 and $T$, where $n$ is the number of desired periods, as defined in Equation 4.4. Its values are rounded down and the first value is fixed to $I_1 = 1$.

$$\mathbf{I} = \begin{cases} I_1 = 1 \\ I_j < I_{j+1} \quad j \in [2, \ldots, n] \\ I_{n+1} = T \end{cases} \tag{4.4}$$

### Step 4 – Index evaluation and performance indicators

**Index evaluation** For each period of the index, the mean values of each profile are calculated and used to construct $r_i(t)$ as seen in Equation 4.5. This corresponds to building a new profile made up of the mean values of the $q_i$ profiles over each period.

$$r_{i,[I_j,\dots,I_{j+1}-1]} = \sum_{t=I_j}^{I_{j+1}-1} \frac{q_{i,t}}{I_{j+1} - I_j - 1} \quad i \in [1, \dots, k] \quad j \in [1, \dots, n] \tag{4.5}$$

**Standard deviation performance indicator – $\sigma$** The standard deviation between the $q_i(t)$ and $r_i(t)$ profiles is calculated for each $k$, shown in Equation 4.6, and the mean value of the $\sigma_i$ serves as the performance indicator, Equation 4.7.

$$\sigma_i = \sqrt{\frac{1}{T}\sum_{t=1}^{T}(q_{i,t} - r_{i,t})^2} \quad i \in [1, \dots, k] \tag{4.6}$$

$$\sigma = \frac{1}{k}\sum_{i=1}^{k}\sigma_i \tag{4.7}$$

**Zero flowrate period indicator – $\Delta$** A tolerance value is defined for each profile to define its cutoff value, for example $\tau_i = 5\%$ of the normalised value. This is necessary as industrial flowmeters do not accurately record nil flowrates. Each time step of the $q_i(t)$ profiles is tested to see if it is smaller than $\tau_i$ (Equation 4.8). The same is done for the $r_i(t)$ profiles (Equation 4.9). The performance indicator measures the number of zero flowrate periods which are not respected, Equation 4.10

$$\begin{cases} q_{i,t} < \tau_i \Rightarrow z_{i,t} = 1 \\ q_{i,t} \geq \tau_i \Rightarrow z_{i,t} = 0 \end{cases} \quad t \in [1, \dots, T] \quad i \in [1, \dots, k] \tag{4.8}$$

$$\begin{cases} r_{i,t} < \tau_i \Rightarrow \bar{z}_{i,t} = 1 \\ r_{i,t} \geq \tau_i \Rightarrow \bar{z}_{i,t} = 0 \end{cases} \quad t \in [1, \dots, T] \quad i \in [1, \dots, k] \tag{4.9}$$

$$\Delta = \sum_{t=1}^{T} \sum_{i=1}^{k} (z_{i,t} - \bar{z}_{i,t}) \tag{4.10}$$

#### Step 5/6 - EMOO

In the EMOO, a population of $u$ random solutions $\mathbf{x}$ is transformed into their corresponding index $\mathbf{I}$ and tested against the performance indicators. The best indexes $\mathbf{x}$ are retained and evolutionary mechanisms are applied to them, for example breeding, mutations and crossovers. The aim is to produce new indexes which perform better than their parents. The process is repeated until $v$ iterations have been completed.

The EMOO produces a Pareto curve of solutions which minimise the performance indicators $\sigma$ and $\Delta$.

#### Step 7 - Choosing the best index

Once $v$ iterations have been completed, the best performers are available for selection. Specific periods can be added into the index of periods manually. This can be interesting to ensure that maximum cluster demand is properly taken into consideration.

## 4.4 Application to Typical Industrial Cluster

Ideally, the representative periods would be identified based on the analysis of all the cluster's data though the task would be daunting. Therefore key drivers of variation of the industrial site are chosen to identify representative periods.

As the thesis principally relate to the steam demand of the industrial cluster, the highest pressure steam flowrate of each PU was defined as the key driver of variation. All PUs were considered to be of equal importance therefore their flowrates were normalised to have a mean value of 1 t/h. Reconciled data was used. Cooling demand was not considered as a key driver of variation for this case study.

The algorithm was run for a number of periods, $p \in [10, 21]$ so as to obtain a better understanding of the possibilities offered by the data. The upper bound was chosen to keep a manageable number of periods.

An initial population of indexes $u = 2000$ was generated for each run of the algorithm, for a total $v = 75000$ iterations. As the algorithm is non deterministic, it was run 3 times for number of periods and the best results were chosen. Each run of the algorithm took approximately 0.8 hours. The data set contains a total of 301 zero flowrate periods.

The results for all of the periods are presented in Figure 4.4. As the EMOO produces a Pareto curve of results minimising the $\sigma$ and $\Delta$ performance indicators, the best results for both are shown for each number of periods. The figure also shows the performance of monthly means (purple hexagon) and weekly means (magenta star). Some results are circled to indicate their corresponding number of periods.

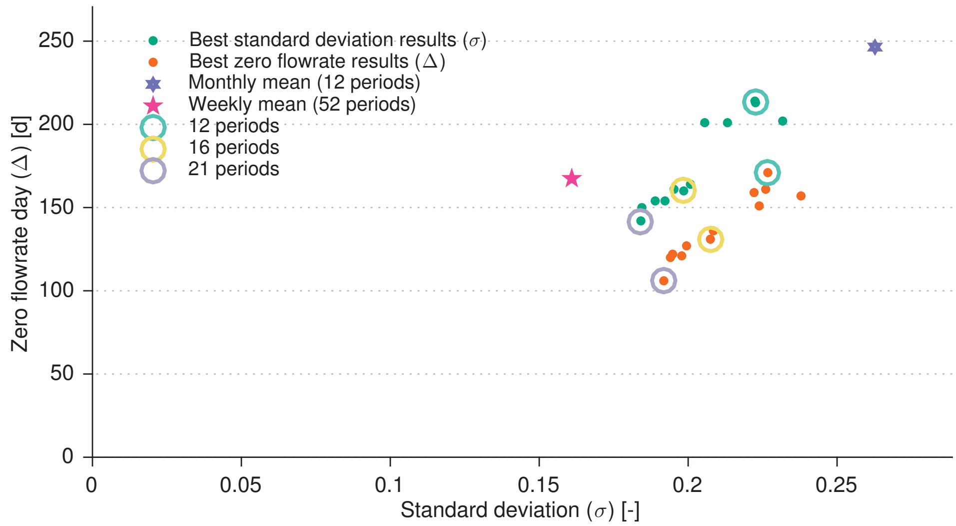



Figure 4.4 – Best performing indexes for $p \in [10, 21]$.

As expected, the results show that as the number of chosen periods increases, the values of the performance indicators improve. Results minimising the $\Delta$ objective have almost the same standard deviation as those minimising the $\sigma$ objective, though their $\Delta$ performance is significantly better.

The monthly mean values produced the worst results with the highest $\sigma$ and $\Delta$ values. The values circled for 12 periods, clearly show the advantages of this method in comparison to using monthly means. The algorithm reduced the number of unmatched zero flowrate periods from 246 to 161 days compared with monthly mean values while reducing the $\sigma$ value by 15.3% .

The use of weekly mean values produced the best $\sigma$ results though zero flowrate periods are well respected.

Figure 4.5 shows the same results as Figure 4.4 for both objectives with respect to the number of periods. The green values show the best index for the $\sigma$ indicator and the brown values show the best for the $\Delta$ indicator. The dotted lines show the performance of weekly and monthly means.

Following an analysis of the performance indicators, the index minimising the zero flowrate performance indicator ($\Delta$) for $p = 17$ periods was chosen to best represent the data, for the following reasons:

1. Graph (a) shows that its $\sigma$ value was equally low as that of the index minimising the $\sigma$ indicator for the same number of periods.

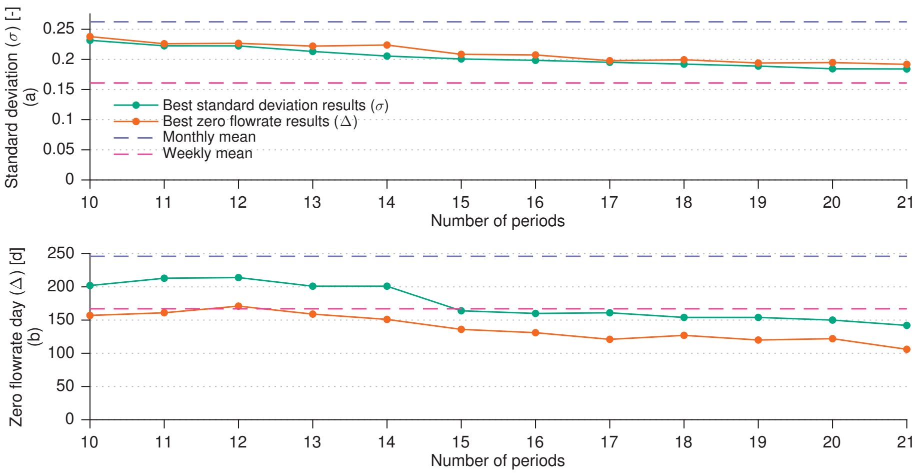



Figure 4.5 – Standard deviation (a) and zero flowrate (b) indicator with respect to number of periods.

2. The $\Delta$ indicator performs less well for $p = 18, 19, 20$ than for $p = 17$.

The period of maximum demand was manually added into the index bringing it to 19 periods. Its mean standard deviation is $\sigma = 0.20$ and $\Delta = 148$ zero flowrate periods are not taken into account by the index (49% of total).

Table 4.1 shows the details of the chosen index and Figure 4.6 shows how they fit on the steam consumption profiles. Its standard deviation is highest during period 18 and 20 zero flowrate periods are not respected in periods 2, 7 and 18.

Figure 4.6 clearly shows the difficult task laid by the problem as many PU shutdowns are present. The worst performance comes from PU F of Site R, with a total of 40 non respected zero flowrate periods. It should also be noted that the peak consumption of PU A of Site P is not well taken into consideration near day 300.

Given the complexity of the data, it is unlikely to be able to significantly reduce the $\Delta$ indicator without drastically increasing the number of periods. 19 periods are therefore chosen as an acceptable compromise.

Table 4.1 – Chosen representative periods and performance indicators.

| Period | Start day | End day | Duration [d] | $\sigma$ [-] | $\Delta$ [d] |
|---|---|---|---|---|---|
| 1 | 1 | 28 | 28 | 0.21 | 9 |
| 2 | 29 | 43 | 15 | 0.14 | 20 |
| 3 | 44 | 77 | 34 | 0.16 | 13 |
| 4 | 78 | 110 | 33 | 0.19 | 14 |
| 5 | 111 | 129 | 19 | 0.16 | 4 |
| 6 | 130 | 133 | 4 | 0.10 | 2 |
| 7 | 134 | 144 | 11 | 0.16 | 20 |
| 8 | 145 | 159 | 15 | 0.13 | 5 |
| 9 | 160 | 176 | 17 | 0.19 | 4 |
| 10 | 177 | 199 | 23 | 0.13 | 1 |
| 11 | 200 | 211 | 12 | 0.08 | 11 |
| 12 | 212 | 219 | 8 | 0.08 | 0 |
| 13 | 220 | 228 | 9 | 0.22 | 6 |
| 14 | 229 | 242 | 14 | 0.17 | 0 |
| 15 | 243 | 243 | 1 | 0.00 | 0 |
| 16 | 244 | 259 | 16 | 0.16 | 9 |
| 17 | 260 | 296 | 37 | 0.18 | 1 |
| 18 | 297 | 327 | 31 | 0.26 | 20 |
| 19 | 328 | 365 | 38 | 0.16 | 7 |

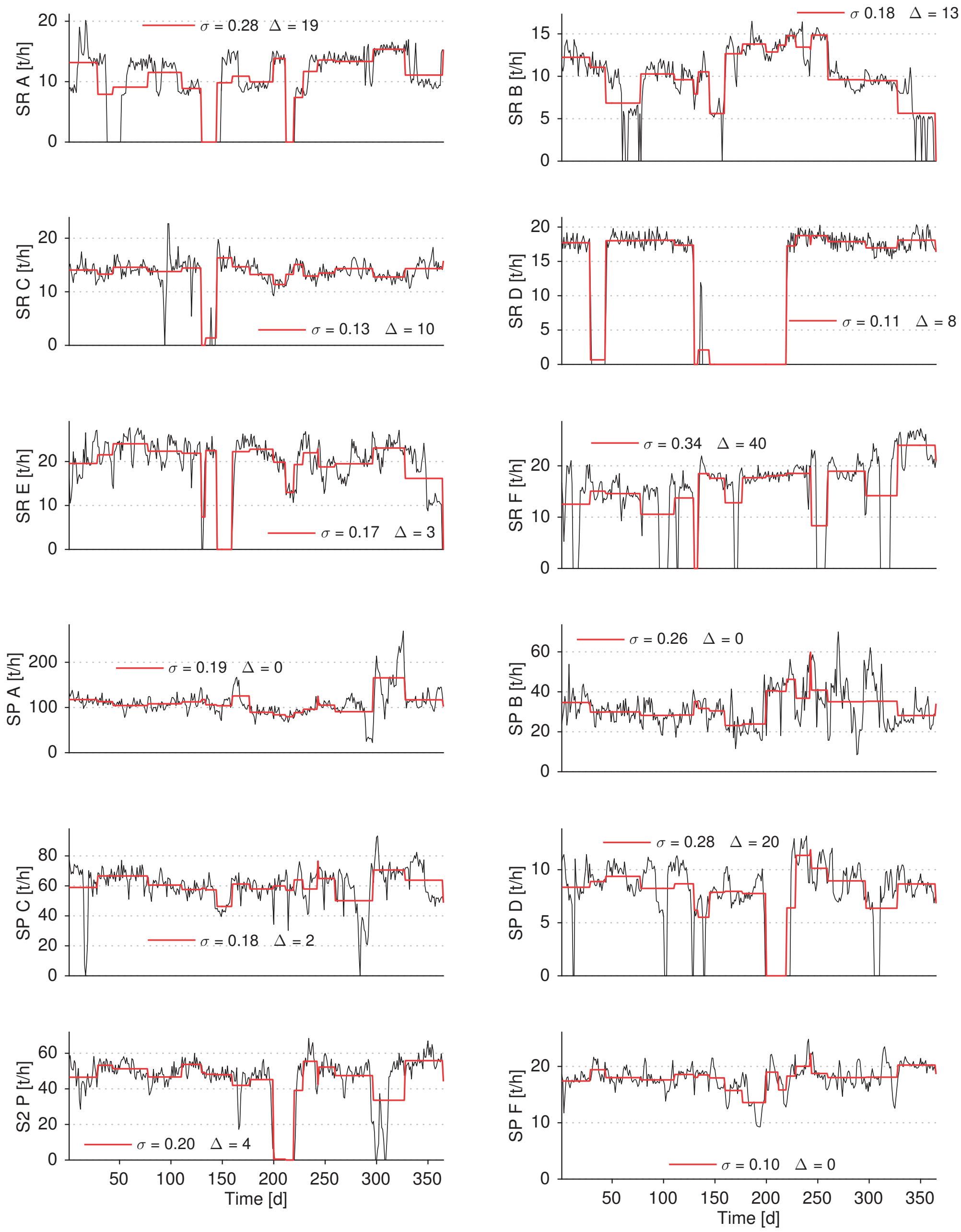



Figure 4.6 – Chosen representative periods of steam consumption profiles using 19 periods.

## 4.5 Conclusion

Given the large amount of available information on industrial sites, engineers must find ways to identify key data in an appropriate resolution. Rather than using the yearly or monthly mean values of data which could potentially over-simplify it, engineers should aim to use scenario based approaches, which permit a better identification of operational modes. These can be exploratory (based on existing data) or normative (predictive of future operations).

Accurately defining such scenarios is time consuming and requires a high level of process knowledge. In the case of an industrial cluster with multiple process units, building such a knowledge base would be challenging. This chapter has therefore proposed a methodology to simplify the task of identifying operational scenarios through a computer aided algorithm.

Using an Evolutionary Multi-Objective Optimisation, multi-time data sets containing multiple profiles can be divided into stable periods from which scenarios can be extracted. The periods are identified using two performance indicators, which ensure closeness of fit between the original profiles and the identified scenarios and that periods of zero flowrates (for example corresponding to a PU shutdown) are respected by the profiles.

This method was applied to the reconciled data of the 12 PUs of the Typical Industrial Cluster and was shown to produce significantly better results than traditional techniques. For example, for 12 periods the algorithm reduced the number of unmatched zero flowrate periods from 246 to 171 days compared with monthly mean values.

To carry out the Total Site Analysis in Chapter 5, the method was used to produce 19 periods of stable operations to be used as operational scenarios. These include the day of maximum cluster demand. Given the important amount of variations and combination of events taking place in the steam demand of PUs, these 19 scenarios are assumed to be normative as well as exploratory.

The method could be further augmented to include outlier removal, for example by excluding periods where the indicators perform badly. Similarly, other heuristic algorithms could be tested to further improve the performance.

# 5 Multi-period Total Site Analysis

*This chapter presents a methodology to apply Total Site Analysis tools to the refining and petrochemical industry.*

## 5.1 Introduction

The aims, developments and limitations of the Pinch Analysis technique are firstly discussed in Section 5.1.1, followed by a discussion on Total Site Analysis in Section 5.1.2. The objectives of this Chapter in are described in Section 5.1.3. The developed methods of Section 5.2 are applied on the Typical Chemical Cluster in Section 5.3 and 5.4. Lessons learned from industrial applications and easy win retrofit solutions are described in Section 5.5 followed by a conclusion in Section 5.6.

### 5.1.1 Pinch Analysis

Pinch Analysis is a technique for the design and retrofit of heat exchanger networks, developed by Bodo Linnhoff [17]. It guides engineers towards maximising heat recovery from processes and therefore an increase in energy performance of their Process Units (PUs). This is achieved through optimal design of heat exchanger networks, which match process hot sources to process heat sinks.

In laymann's terms, the Pinch Analysis technique shows engineers how to build heat transfer systems which maximise the internal recovery of heat. It ensures that high quality heat (high temperature) is used only on process streams requiring high temperatures. In a similar way, cold sources are used where low temperature cooling is needed.

According to the Pinch Analysis technique, maximum recovery is achievable through the implementation of an optimal heat exchanger network. Through the analysis of the Composite Curves (CC) and Grand Composite Curves (GCC) resulting from the Pinch Analysis, the following key system properties can be calculated [54]:

- $MER_H$: Minimum Energy Requirement for Heat. This corresponds to the theoretical minimum heat required for a PU to operate. It is achieved if process streams are connected through a thermodynamically optimal heat exchanger network to maximise heat recovery.
- $MER_C$: Minimum Energy Requirement for Cooling. The theoretical minimum cooling requirements of a PU, reached through thermodynamically optimal design of heat exchanger networks.
- Pinch point: The pinch point defines the temperature at which heat exchange within a PU is most complicated. The PU's heat exchanges can theoretically be divided into two independent sub-systems above and below this temperature, through which heat should not be exchanged. The system above the pinch point is a heat sink, the system below is a heat source.
- Penalising heat exchangers: In the case of system retrofit, a list of penalising heat exchangers can be made. These are the exchangers which transfer heat across the pinch point and thereby increase the overall requirements for heating and cooling of the system.

A retrofit operation on the heat exchanger network should firstly have for aim to eliminate the heating and cooling penalties, leading to direct energy bill reduction.

Industrial sites and clusters are made up of multiple PUs, some of which may belong to different business units, separated by important distances. Pinch Analysis identifies the potential for direct Process Integration with PUs and is not always adapted to such scales, some of the reasons are detailed below:

1. Flexibility: PUs are complex systems operated by skilled engineers and operators. Some PUs require relatively constant amounts of heating and cooling, while others have a varied demand. Some PUs shut down regularly while others seldom do [34]. Process Integration between sub-units between PUs reduces the flexibility of operations as they are made interdependent. In such cases, variations in one PU's operations can lead to over or under-supply of cooling and heating in its neighbours.

   Long term reliability should also be a concern for businesses investing in equipment. As dependence between PUs increases, operations must remain viable despite future events. For example, a PU going out of business or changing operations could impact integration measures [40].

2. Space: PUs are often compactly built to minimise land use. Proposals for heat exchanger modifications are only feasible if space for the solutions exists (new heat exchanger and piping).

3. Losses: The transport of process streams is inevitably associated to thermal and pressure losses. Temperature decrease in long pipes can have obvious effects on nullifying and even reversing the effects of heat exchanges (when the approach temperatures are small). Similarly, pressure losses may need to be compensated with pumps and compressors, requiring additional energy.

4. Safety: Leaks and punctures of heat exchangers can lead to potentially dangerous substance mixing. As a safety measure, a certain distance is therefore kept between certain streams. Safety engineers will also ensure that exothermic reactions susceptible to thermal runway are cooled using highly dependable cooling water rather process integration [67].

5. Complexity: With hundreds of heat exchangers to consider, Pinch Analysis studies can quickly become challenging. Generating energy efficiency solutions manually through heat load diagrams is laborious work.

6. Capital costs: The transport of fluids across distances has an important capital cost with investments required in pipes, pumps, compressors and control systems and other equipments. Pinch Analysis solutions implemented by industrials should ideally have positive economic returns, which may not always be the case when integrating between PUs and sites.

These 6 points can be seen as the constraints and limitations of the application of Pinch Analysis to industrial sites as a whole. Point 3 (losses) is a constant constraint. Point 4 (safety) offers little margin for flexibility, especially given the volatile nature of products handled in the refining and petrochemical industry.

The other constraints can eventually be bypassed through improved control systems, better process knowledge and a mentality shift of engineers and operators, for example through incentives [56]. It is important to note that operators have the obligation to maintain the safety of their plants, reach their production targets and only then reduce costs.

### 5.1.2 Total Site Analysis

Total Site Analysis (TSA) was developed to implement the Pinch Analysis theory in industrial sites while relaxing some of the above mentioned constraints. It is an efficient technique for identifying energy saving opportunities industrial clusters. It focuses on the utility systems rather than direct Process Integration between sub-units of PUs. It was developed by Dhole and Linhoff [18] in 1993.

Industrial sites use intermediate utility systems such as steam or a How Water Network (HWN) to transfer heat. For example, boilers can be used to generate steam efficiently and distribute it through a centralised pipe network to the PUs. PUs may also generate excess steam as a result of process cooling, which can itself be sent into the steam network.

Similarly to Pinch Analysis, TSAs calculate the $MER_H$ and $MER_C$ of industrial sites and clusters, which can be compared to their energy bills. The benefits of the TSA technique have been demonstrated in petrochemical sites and heavy chemical sites [77] by retrofitting existing utility systems and reducing energy bills. Reduced consumption also leads to $CO_2$ emissions reductions [76].

As a design tool, TSAs have shown the benefits of using cluster wide utility systems despite PUs belonging to different businesses [72]. Sensitivity analyses have also shown that proper sizing of back-up boiler systems can allow utility system to remain operational despite PU turnarounds or decommissioning [40]. Appropriately choosing steam turbines to cogenerate power was also shown to significantly reduce operational costs [77].

Given the complexity of industrial clusters and their variations through time, single-period TSAs run the risk of undersizing solutions. Using a multi-period approach, it is possible to better understand the systems and increase the accuracy of its thermodynamic results as well as generated solutions [40].

The use of linear and non-linear mathematical optimisation methods has led to significant improvements to the method. Becker and Maréchal developed the Restricted Matches method to optimally design heat exchanger networks within PUs. The remaining energy demand is met through a shared utility system [71].

Further developments proposed heat exchanger networks which optimally maximise Process Integration between sub-units of PUs, based on topological criteria [68]. The remaining demand is met by a shared utility system.

A very significant contribution has been to design thermo-economically optimal steam network pressure levels for shared utility systems [64]. This method is best applied in the case of network conception rather than retrofit. Combined with mathematical formulations to optimally place cogeneration devices industrial sites [73] it is possible to produce optimal steam networks which maximise cogeneration of heat and power.

The TSA method and its developments address many of the limitations of the direct application of Pinch Analysis to industrial sites. Concerns over lack of space, flexibility and capital costs are addressed through thermo-economic optimisation. Pressure and thermal losses are respectively resolved through the use of utility networks and intermediate heat transfer systems. As safety cannot be compromised on, it is important to involve safety engineers in the design of systems which maximise the potential for heat recovery.

Several aspects of the TSA do however remain problematic:

- Increased losses: By passing through an intermediary heat transfer fluid, additional thermal losses may occur as well as an increased overall approach temperature, which reduces the available exergy.

- Data: Collecting the required data can be very time consuming and complicated as each PU must be analysed independently and may belong to different business units.

  Data quality issues are a permanent problem and tools are needed to identify which data must be collected and how to include it in a TSA. Chapter 3 has already focussed on improving the quality of steam network data.

- Business accords: Negotiating investment agreements and payback terms between business units with varied financial strategies exits the scope of engineering problems, It is however a major barrier to implementation of solutions [72]. Engineers should therefore take care to generate results that give suitable input to decision makers.

- Regulatory framework: Given the complex regulatory framework concerning greenhouse gas emissions, implementation of TSA solutions between businesses are bound to complicate the allotment of emissions allowances.

### 5.1.3 Objectives

As business accords and emissions regulations leave the scope of this thesis, this chapter focuses on the problematic of data acquisition and modelling. Section 5.2 proposes a methodology to model and treat several types of heat producers and consumers identified in the refining and petrochemical industries.

This methodology is applied to the Typical Industrial Cluster (TIC) case study in Section 5.3. As a result of the generated TSA CCs and GCCs, a proposition for retrofitting the TIC is made to improve energy performance in Section 5.4. The case study is carried out in multi-period form thanks to the formulations of Chapter 4.

## 5.2 Methodology

Carrying out a TSA requires temperature-enthalpy profiles to be established for the utilities and the processes they deliver and receive heat from. As in the Pinch Analysis technique, the CCs and GCCs for processes and utilities can be plotted [72].

Thanks to the dual representation of processes by their thermal and utility requirements [86], either the process or the heat transfer fluid can be used to calculate the energy exchanged, reducing data collection requirements. For example, if the amount of steam delivered to a process is known, the amount of energy delivered to it is also known.

As TSAs do not take into consideration direct Process Integration, many process streams do not need to be represented at all. This greybox approach to industrial sites [85] makes the task of data collection much simpler.

A setback of the greybox approach is that it neglects heat recovery potential through direct Process Integration and therefore only identifies a certain proportion of heat recovery options. This methodlogy therefore assumes that investments in direct heat exchange are already made for each PU prior to investigating the site-wide solutions.

Concerning data collection, care should be taken to apply the 80/20 rule [86], otherwise known as the Pareto principle, coined by Juran in 1950 [87]. This rule of thumb applied to TSAs implies that 80% of energy consumption is caused by 20% of the consumers. However, to close mass and energy balances, 100% of the steam demand must still be identified. The following is therefore proposed:

1. Identify all heat sources connected to utility production (heat recovery, steam generation, hot water production).
2. Identify as many heat sinks as feasible (using the 80/20 rule). The remaining difference can be assumed to be a process at the temperature of the utility.

As covered in Chapter 3, Data Reconciliation has an important role to play in ensuring that the quality of data being used remains high, as well as to calculate unknowns.

Given the large number of utility consumers and producers on industrial sites and clusters, a methodology is proposed to model their temperature-enthalpy profiles. Guidance is given on which thermal sources should be used, where they can be found and what data to collect from them in Section 5.2.1. Nine categories of common heat transfers are identified as well as their temperature-enthalpy profiles in Section 5.2.2.

### 5.2.1 Data collection

The following data should be collected before any TSA can be carried out.

1. Steam network layout:
   - Headers: Locations of headers and their interconnections must be identified to obtain a proper understanding of the steam network. This is true for the site utility network as well as within PUs.
   - Turbines: Flowrates, activation rates and isentropic efficiency of turbines should be obtained when available.
   - Letdowns: Flowrates through letdowns, desuperheating temperatures and demineralised water flowrates will allow for steam temperatures to be calculated in the absence of header measures.
   - Measures: Flowrate, temperature and pressure measures should be identified as well as their locations. This will allow for thermal and pressure losses to be calculated.
2. Steam boilers
   - Superheated steam: Generally produced in centralised boilerhouses or in processes with very high temperature excess heat from furnaces, for example in a catalytic cracker. Flowrates, pressures and temperatures should be obtained when available.

   - Saturated steam: Generally produced within PUs with high temperature exothermic reactions. Flowrates, pressures and temperatures should be obtained when available.
3. Steam consumers:
   - Heat exchangers: Heat exchanger locations and properties must be obtained when available as well as their flowrates. In the absence of measured data, the properties of the process fluids and design data can be valuable. These include its composition, pressure, temperature and flowrate. If the heat exchanger is connected to a condensate return, this should be noted.
   - Steam stripping: The flowrate of steam should be noted, as well as the pressure of the vessel into which it is injected. If no pressure measures are available, design values can be used.
   - Reboilers: The flowrate of steam and the temperature of the bottom of the distillation column should be noted. Temperature readings at the outlet of the reboiler are rarely available.
   - Tracing: The flowrate of steam is rarely measured on tracing, though it can be significant for certaindustrial sites. If bundled measures are available they may be used to make assumptions. The temperature of the fluids in storage tanks and pipes should be noted.
   - Other: Other consumers such as steam hoses should be identified and their flowrates calculated or measured if possible.
   - Steam leaks and traps: As described in Chapter 3, the steam losses can be estimated through Data Reconciliation. These losses can consume significant amounts of steam and should therefore be included in the TSA.
4. Water, steam and cooling cycles:
   - Makeup water: The flowrate and temperature of makeup water imported by an industrial site should be measured.
   - Condensate return: While individual condensate returns by heat exchangers and tracing may be measured, this is often not the case. A global measure of condensate return flowrate to the degassing plant as well as their temperatures may be available.
   - Degassing: Steam injected into the demineralised water in the degassing plant is usually measured as it can be significant.
5. Water coolers: The water flowrate and temperatures as well as those of the process fluid should be noted. In the absence of water flowrate, process properties (pressure, flowrate, temperature and composition) can help to calculate the energy transferred.
6. Aero coolers: The properties of the process are necessary to accurately calculate the energy transferred in an aero cooler.
7. Internal Cooling loops: These loops are usually connected to a water cooler. The internal loop flowrates and temperatures can be used to calculate energy transfers in the absence of other data.

8. Refrigeration cycles: Sub-atmospheric heat sources and sinks may be required in petrochemical sites. For example, products of thermal cracking may be distilled at temperatures of 100°K [58] and may therefore need refrigeration cycles. The properties of such cycles should be treated in the same way as a high temperature heat source.

### 5.2.2 Temperature-enthalpy profiles cases Total Site Analysis

Several typical heat exchanges identified in refining and petrochemical sites are detailed below. For each case, process and utility modelling strategies are proposed.

#### Heat transfer fluid

Two examples of heat transfer fluids are modelled in Figure 5.1, which shows their temperature-enthalpy profiles.

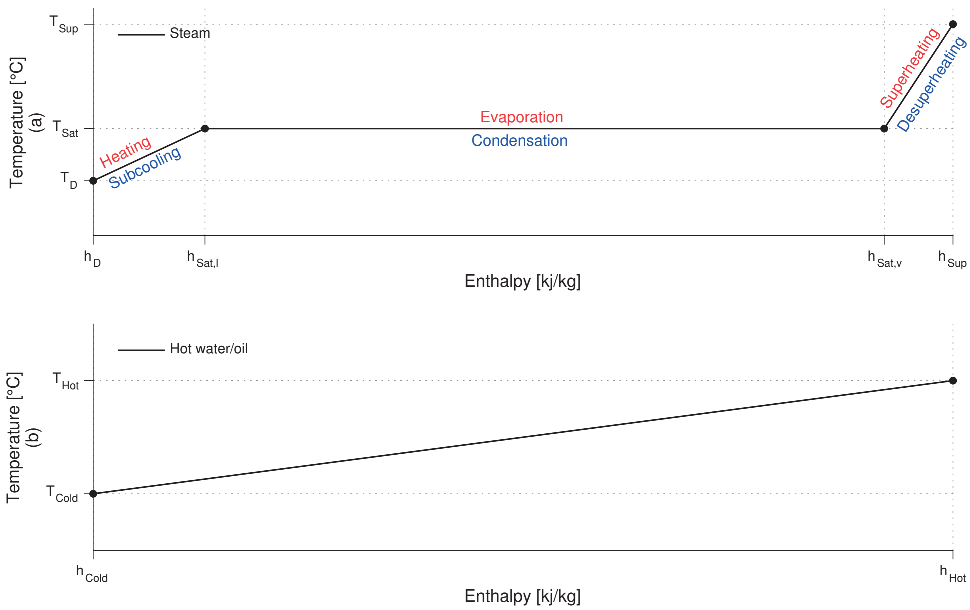



Figure 5.1 – Modelling of superheated steam (a) and hot water/oil stream (b) heat transfers.

In graph (a), superheated steam is shown between its superheated temperature $T_{sup}$ and its lowest temperature $T_D$ (either the desuperheating temperature $T_{Des}$ or that of the demineralised water $T_{Demin}$). The vocabulary for steam production is shown in red and that of steam consumption in blue.

When generating steam, hot demineralised and pressurised water at temperature $T_{Demin}$ is heated to saturation temperature $T_{Sat}$. It is evaporated and superheated to $T_{Sup}$. Steam produced in a boiler is generally superheated, though this is not always the case for steam generated by heat integration.

When consuming steam in a heat exchanger, it desuperheats from $T_{Sup}$ to $T_{Sat}$ and condenses releasing its latent energy. Depending on the heat exchanger, it will then be sub-cooled to $T_{Des}$, its desuperheating temperature.

$h_D$ represents the enthalpy of the water at $T_D$, while $h_{Sat,l}$ is the enthalpy of water at $T_{Sat}$ before evaporation. $h_{Sat,v}$ is its enthalpy when fully evaporated. $h_{Sup}$ is the enthalpy of the steam at $T_{Sup}$. The total energy transmitted to or from steam is the difference between $h_{Sup}$ and $h_D$. The thermal capacity of water and steam are assumed to be constant outside of the evaporation phase.

Graph (b) of Figure 5.1 shows the temperature-enthalpy profile for hot oil or HWNs. The fluid can be heated or cooled between its hot $T_{hot}$ and cold $T_{cold}$ temperatures. The thermal capacity of water and oil are assumed to be constant between the cold and hot temperatures. The energy transferred to and from the fluid is its difference in enthalpy when $h_{hot}$ and cold $h_{cold}$.

Hot oil networks do not need to be pressurised and can transfer heat between 10°C and 400° [79]. HWNs must be pressurised if their $T_{hot}$ is above 100°C. For example, water pressurised at 10 bar can be used at up to $T_{hot}$ =180°C [80].

As steam is the major focus of the work, it is used as the heat transfer fluid for all the examples below. All graphs show the temperature-enthalpy profiles $T(h)$ for the process and utilities as well as their corrected temperature profiles $T^*(h)$.

Corrected temperature profiles correspond to the apparent temperature of streams as they go through counter-current heat exchangers, defined through their individually identified approach temperatures $\Delta T_i$. To obtain the corrected temperature-enthalpy profiles, the $\Delta T$ is subtracted from each hot stream and added to each cold stream, Equations 5.1.

$$T^*_{hot} = T_{hot} - \frac{\Delta T_{hot}}{2} \quad \forall \text{hot streams}$$
$$T^*_{cold} = T_{cold} + \frac{\Delta T_{cold}}{2} \quad \forall \text{cold streams}$$

### Steam generation

Figure 5.2 shows the thermal profile of steam generated in an evaporator and superheater.

The generation of superheatead steam requires hot water to be passed through an evaporator and superheater. In the case where the steam pressure is not recorded, it is assumed to be that of the header into which it is released.

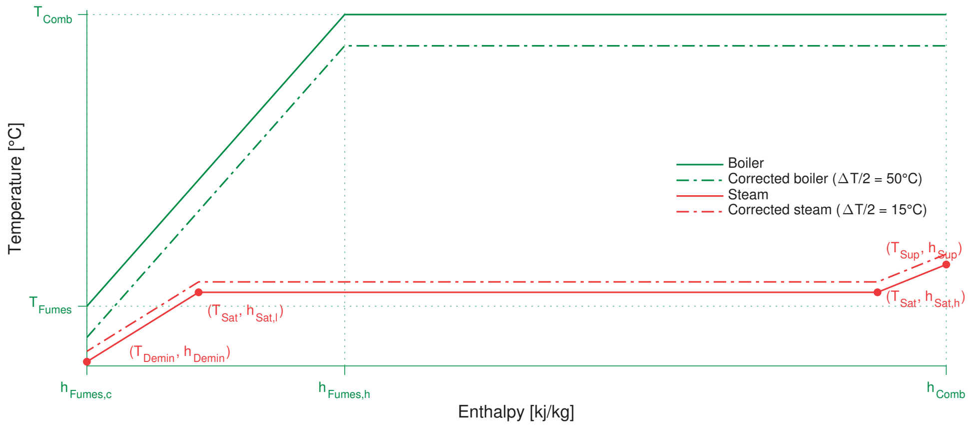



Figure 5.2 – Modelling of superheated steam generation.

In the case of a boiler, above the adiabatic combustion temperature $T_{Comb}$, radiation is predominant, with little part played by convection. As the assumed use of counter-current heat exchangers above these temperatures is not valid, a straight line is used for the heat of combustion [1]. The fumes exiting the combustion chamber are cooled to their outlet temperature at the bottom of the chimney, $T_{Fumes,c}$.

The total energy delivered through the evaporator and superheater is best calculated through the generated steam, which is usually measured. This leads to the assumption in Equation 5.2, where $H_{Boiler}$ is the energy delivered by the boiler and $m_{Steam}$ is the quantity of steam generated. Care should be taken with boilers which reinject demineralised water into superheated steam to control its temperature and quality.

$$H_{Boiler} = (h_{Sup} - h_{Demin}) \cdot m_{Steam} \tag{5.2}$$

Figure 5.3 shows the thermal profile of saturated steam generation by a process flow with constant thermal capacity in a counter-current heat exchanger. Demineralised water is heated to $T_{Sat}$ and evaporated. The temperature of the generated steam is $T_{Sat}$. The overall amount of energy transferred can be calculated using either the steam flow or the process flow, depending on which one is measured.

In this example the process is assumed to have a constant thermal capacity, though in another case it could very well include a phase change.

1. For readability purposes, the real adiabatic combustion temperature is not used in CCs. The maximum process temperature can be used instead.

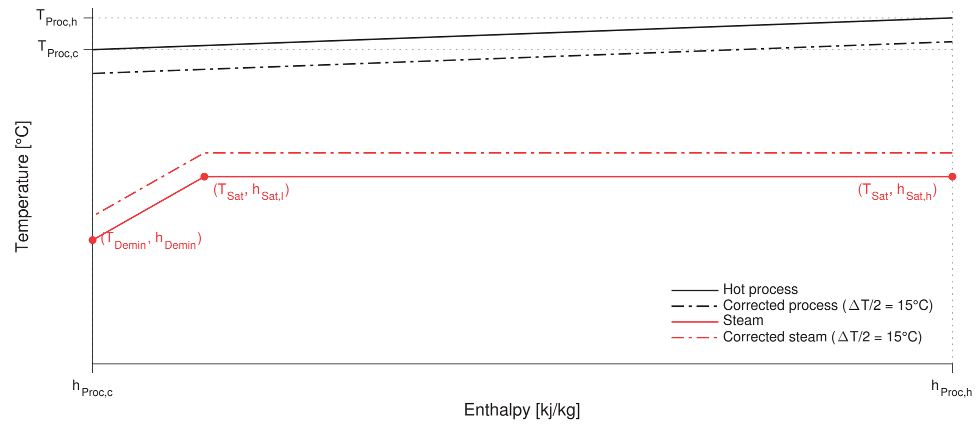



Figure 5.3 – Modelling of saturated steam generation by a process with constant thermal capacity.

### Process evaporation

Figure 5.4 shows the thermal profile of the evaporation of a single phase process stream by superheated steam. It is assumed that the steam pressure is the same inside the heat exchanger as upstream of it. The process fluid is heated, evaporated and superheated. The total amount of energy transferred can be calculated using the steam or process properties. In the case where little is known about the process, assumptions may have to be made on its latent and specific heats.

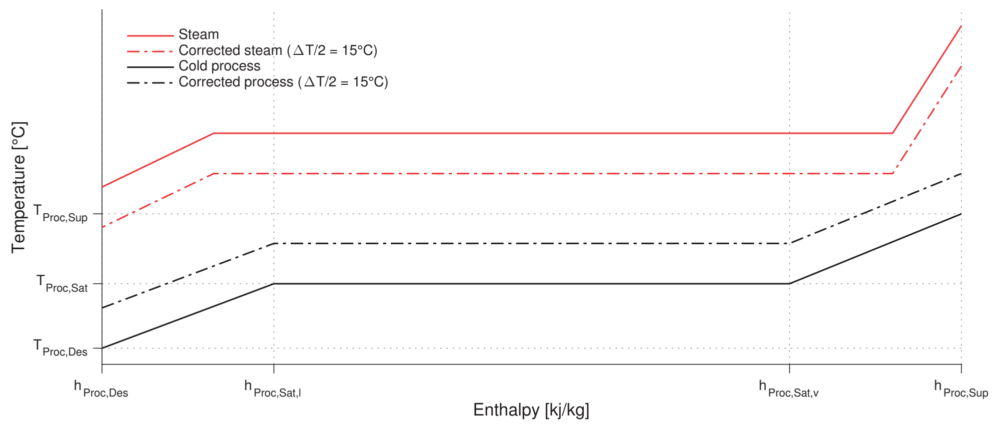



Figure 5.4 – Modelling of single phase process evaporation by superheated steam.

Figure 5.5 shows the evaporation of a multi phase process stream using superheated steam. As is often done in the refining and petrochemical industries, True Boiling Point (TBP) definitions are used to model the process flow [81].

As hydrocarbons are made up of millions of different chemicals, TBPs are an efficient way of characterising their thermal properties. They represent the fraction of fluid evaporated at a given temperature and pressure. Table 5.1 shows the TBP properties used for this example (kerosene evaporation). These must be adapted for the type of hydrocarbon and its pressure.

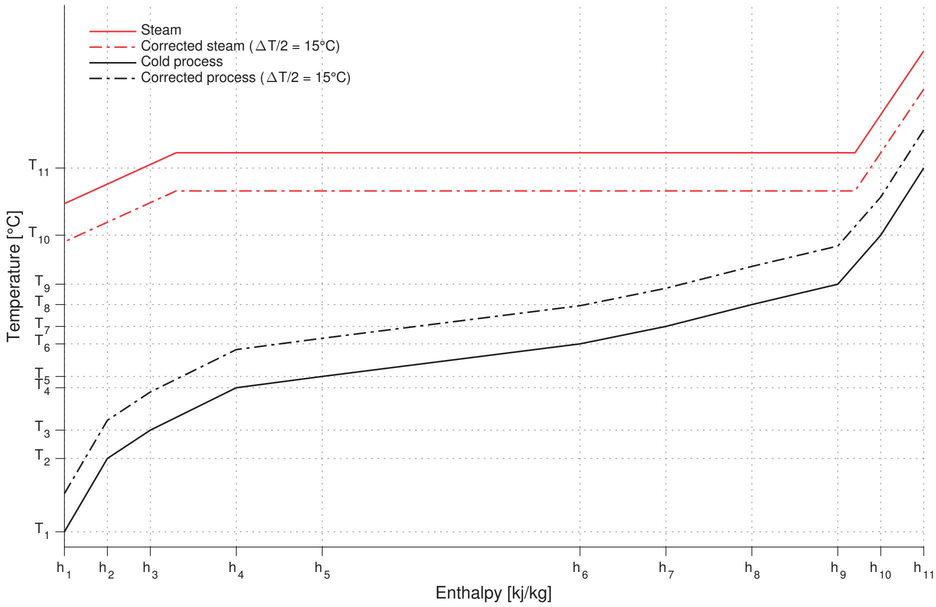



Figure 5.5 – Modelling of multi phase process evaporation by superheated steam.

The quantity of transferred energy can be calculated using the steam properties or the hydrocarbon properties, though the later is more complicated as the constant thermal capacity assumption is no longer valid. Certain flowsheeting softwares offer the possibility to model hydrocarbons using pseudo-component definitions based on their TBPs and thereby calculate their thermodynamic properties [82].

Table 5.1 – True boiling point properties of Kerosene at atmospheric pressure.

| Point | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Temperature | 75.5 | 89.9 | 95.5 | 103.8 | 106 | 112.4 | 115.9 | 120.2 | 124.2 | 133.8 | 147 |
| Evaporated [%] | 0 | 5 | 10 | 20 | 30 | 60 | 70 | 80 | 90 | 95 | 100 |

This sort of modelling can be applied to distillation column reboilers, in which a process is heated between $T_{Column,bottom}$ and $T_{Column,bottom} + \Delta T$.

### Steam stripping

Steam stripping (also referred to as injection) is a common process in refineries and petrochemical sites. Steam is injected into distillation columns to separate volatile components from a liquid mixture. The steam reduces the partial pressure of the mixture and therefore reduces the evaporation temperature of its components [83]. Figure 5.6 shows the thermal profile for steam stripping.

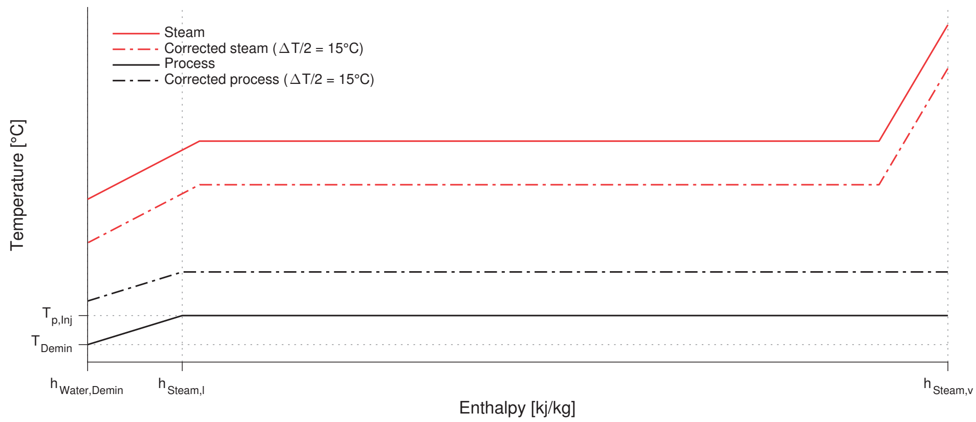



Figure 5.6 – Model of steam stripping.

The process requirement can be defined as saturated steam at a pressure above that of the vessel's pressure, as seen in equation 5.3, where $p_{Vessel}$ is the vessel's pressure and $\Delta p$ is the required overpressure, which is specific to each vessel. In certain cases steam stripping may also be needed to contribute heat towards the vessel, superheating of the steam may then be required.

$$p_{Steam,Inj} = p_{Vessel} + \Delta p \tag{5.3}$$

Steam injected into a column generally exits the top of it where it may then be cooled and separated. This cooling must be taken into consideration to respect the overall mass and energy balance of the system.

### Losses

Losses can be considered to be a requirement of the utility network. As the lost fluid is delivered to the atmosphere, it is considered to be the process requirement. The quantity of energy transferred is equal to that of the lost fluid. Figure 5.7 illustrates the temperature-enthalpy profiles for steam losses.

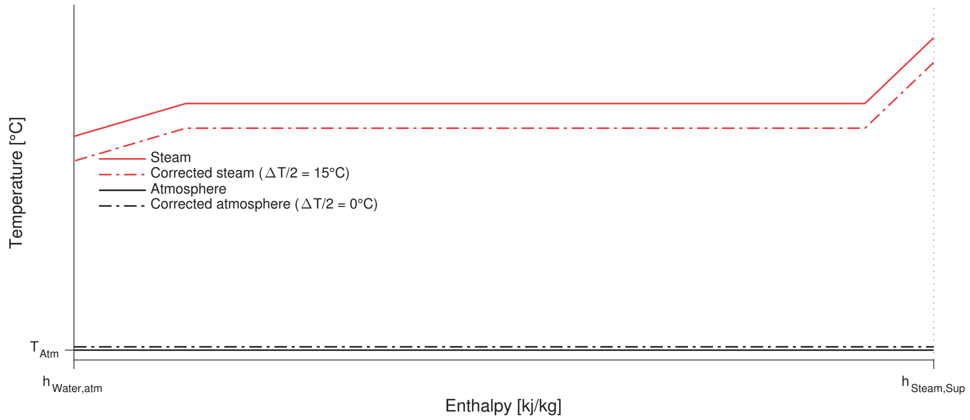



Figure 5.7 – Modelling of steam leaks.

### Tracing

The aim of pipe and tank tracing is to maintain a fluid at a given temperature, to prevent congealing and associated pressure losses. The process requirement of tracing is therefore defined as heat delivery to the fluid at its current temperature $T_{Fluid}$ [83]. Figure 5.8 illustrates the temperature-enthalpy profiles for steam tracing.

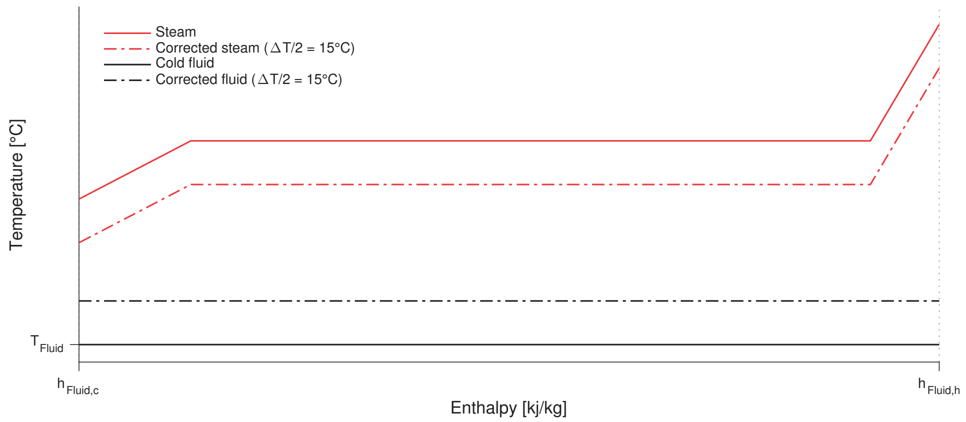



Figure 5.8 – Modelling of steam tracing.

Steam hoses can be considered in the same way as steam tracing, though at atmospheric temperature.

### Utility cooling

Cooling can be used to condense process streams or to cool them down, for example before storage. Figure 5.9 models a process stream defined by TBPs, cooled either by aero-cooling or water-cooling.

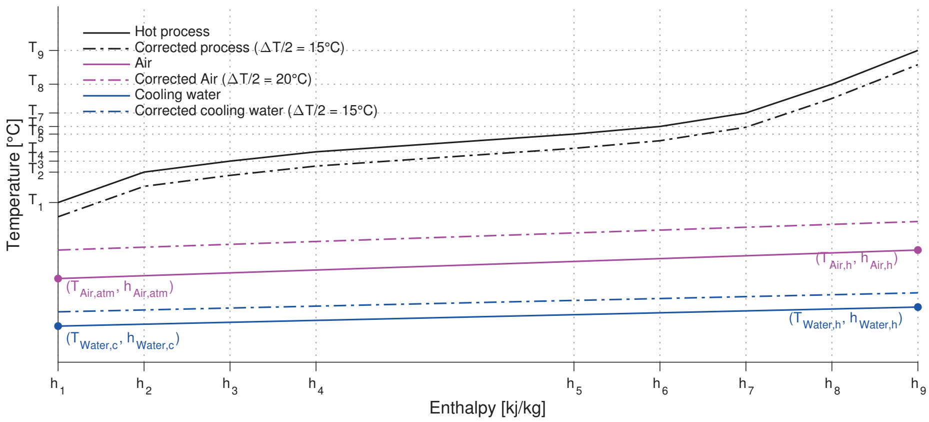



Figure 5.9 – Modelling of aero and water-cooling of process streams.

In water-cooling, hot process streams are run through pipes exposed to flowing cold water. Cold air can be used to evacuate the heat from the hot water, before it flows into a basin where it further cools. It is then pumped back towards the exposed pipes. The water is heated from $T_{Water,c}$ to $T_{Water,h}$ between $h_{Water,c}$ and $h_{Water,h}$. If the flowrate and temperatures of water are known, the transferred energy can easily be calculated, otherwise process properties are required.

Aero-cooling is technically simpler as cold air at atmospheric temperature $T_{Atm}$ is fanned onto exposed pipes to cool them, raising the air temperature to $T_{Air,h}$, between $h_{Air,atm}$ and $h_{Air,h}$. Design values of the aero cooler can be used to estimate the energy transfer between air and process streams, though it is best to model the process for more accurate results.

In petrochemical sites, primary cooling loops are often used to cool down sensitive reactors, for example in the case of polymerisation. This internal cooling loop is itself cooled down by a secondary water-cooling cycle. As polymerisation is a sensitive process, safety engineers must control its temperatures accurately and without disturbances, which justifies why direct process-utility contact is forbidden. As a result, much of the available exergy is destroyed. The primary cooling cycle is included in the TSA rather than the reactor's heat, as it is not available as a usable heat source.

### Turbines

The Pinch Analysis technique focuses on heat exchanges and does not include cogenerated power. This power can however be the subject of thermo-economic optimisation combined to Pinch Analysis [73] and is therefore interesting to show in the Pinch Analysis results. Figure 5.10 shows a schematic of the conversion of High Pressure (HP) steam into Low Pressure (LP) steam through a turbine.

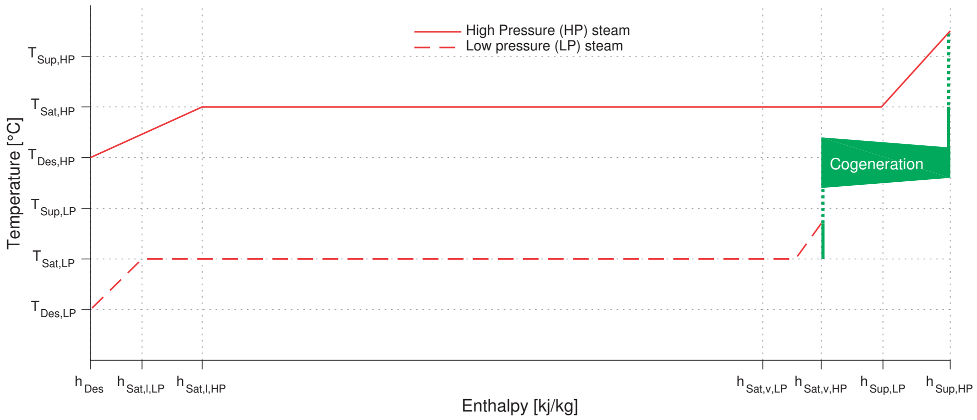



Figure 5.10 – Schematic of mechanical power conversion by a turbine.

The red curve shows the enthalpy of the inlet and outlet steam at their different stages. The HP steam (inlet steam) enters the turbine and exits it at a lower pressure. A portion of its energy is converted into mechanical energy, The LP steam's enthalpy is therefore reduced compared to that of the HP steam.

The solid green lines indicate the pressure difference between the inlet and outlet steam. The dotted green lines indicate their superheating temperatures. The superheated temperature of the LP steam $T_{Sup,LP}$ and mechanical power conversion depend on the isentropic efficiency of the turbine, the difference in pressure between steam levels and the superheating level of the HP steam.

This representation cannot be shown in the CCs and GCCs directly as it would amount to showing the same load twice, however the mechanical power (in green) can be shown next to the curves to quantify how much of the overall energy contributes towards cogeneration.

### Letdowns

Letdowns are not visible in TSA results. Some of them may be desuperheated at their outlets while others may not, thus influencing the superheating temperature $T_{Sat}$ and therefore enthalpy of the lower pressure steam levels.

#### Site utilities and water cycle

To close the energy balance of the industrial site or cluster it is necessary to consider the condensate returns of steam, the preparation of the demineralised water and the pre-heating of the makeup water. These are referred to as the site utility consumptions. Two methods exist:

1. Modelling of each individual stream: For each steam consumption, it should be known whether or not condensates are returned. If they are returned, degassing should be modelled in the form of an injection. If the condensate is not returned, its equivalent in makeup water should be modelled between $T_{Cold}$ and $T_{Demin}$ followed by degassing. Steam losses must be considered as steam without condensate return.

   Drawbacks of this method are that it assumes linear degassing requirements with respect to the steam output, which may not be verified in practise [77]. Demineralisation plants may vary significantly from site to site. Some may require returned condensates to be fully cooled before being degassed, which may not be necessary in others.

2. Model for entire site based on data: Industrial sites usually have measures on makeup water flowrate, steam stripping flowrate for degassing and overall condensate returns. By modelling the thermal exchanges on these streams directly based on measured data, overall energy balances will be closed.

   The principal drawback of this method is that it may complicate the task of estimating the impacts of heat exchanger modifications to the system. For example, if one implements a steam demand reduction, the degassing requirements must also be reduced. The quantity may be estimated, though its accuracy can be questioned.

### 5.2.3 Implementing a Total Site Analysis

Once all data has been collected, its coherence should be verified before the CC and GCC curves can then be generated.

#### Stream verifications

It is recommended to perform an analysis on all streams for each time period before carrying out any TSA, to establish if the heat exchanges are feasible. As counter-current heat exchangers are the most commonly used for utility consumption and production, graphical analysis of the temperature-enthalpy profiles can provide this information. This task is simplified as dual representations (process and utility) are systematically defined and necessary for all streams in a TSA.

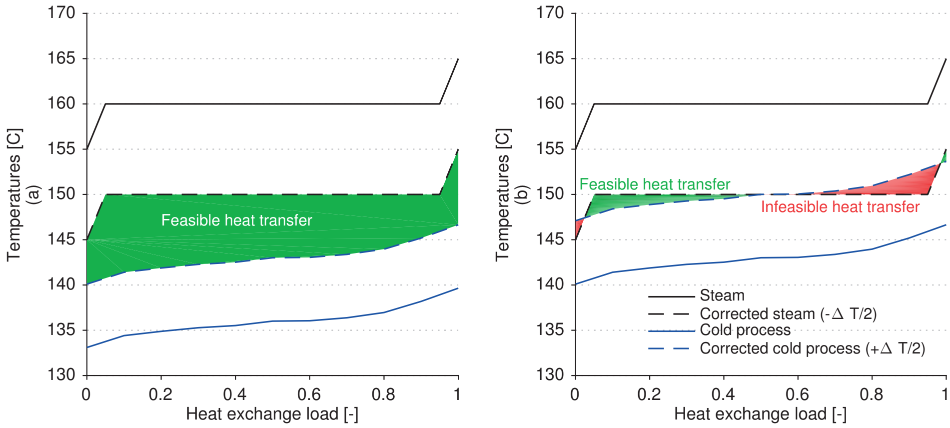



Figure 5.11 – Schematic of feasible (a) and infeasible (b) heat transfer using steam.

Figure 5.11 illustrates two cases of counter-current heat exchanges. The graphs show the process and utility temperatures and corrected temperatures in dotted lines. In graph (a), steam is used to heat a process. The corrected temperature of the process remains well underneath that of the corrected steam for its entire load, making it feasible. Graph (b) shows an infeasible heat exchange as the corrected temperatures overlap in the red areas.

By using this sort of analysis to identify infeasible heat transfers, it is possible to make sure that the existing streams are correctly defined and that any modifications to the utility networks are feasible.

### Generating Total Site Analysis results

A TSA shows the interactions between process and utility networks. This is achieved through a graphical representation of the heat loads exchanged between the process and utilities of a system. Based on the Pinch Analysis technique, these representations are achieved through the creation of a heat cascade, which sorts the heat production and requirements of processes according to their temperatures [17]. The temperature-enthalpy definitions of all streams are therefore necessary.

The TSA results can be achieved in a four part process:

1. Generation of process curves: As in a Pinch Analysis, heat source and sink profiles are created for the process, using corrected temperatures.
2. Matching of process curves with utility curves: Process heat sources and sinks are respectively matched to their cold and hot utilities. The aim of this step is firstly to verify that the temperature-enthalpy profiles of the processes and utilities are compatible.

   Secondly it ensure that the energy balance is closed between process requirements and utility supply. The process and utility curves should never overlap and their total loads should be identical. If the dual representation shown in Section 5.2.2 has been used and verified as recommended, no errors should be found.

3. Compiling of process and utility curves: The process-utility curves generated in step 2 can be slid together until the hot utility curve touches the cold utility curve.
4. The GCCs of the utilities are equal to the difference between the hot utility and cold utility CCs. The process GCCs are the difference between the hot process and cold process CCs.

The total cogeneration power of a system can be plotted by the CCs and GCCs to more accurately represent the overall boiler supply.

### 5.2.4 Total Site Analysis example

An example is given to illustrate the expected results from a TSA. Table 5.2 details 10 steam consumers and producers on an imaginary industrial site. The site produces steam in a boilerhouse at 90 barg and 450°C, supplying 25 t/h of steam. A turbine extracts power from this steam and releases it at 20 barg.

Blue indicates hot process streams to be cooled, and red indicates cold process streams to be heated. The table shows which utility is used and at what temperature, the energy transfer and the process inlet and outlet temperature. In the example, makeup water is required as some condensed steam is not returned. All demineralised water is degassed before evaporation.

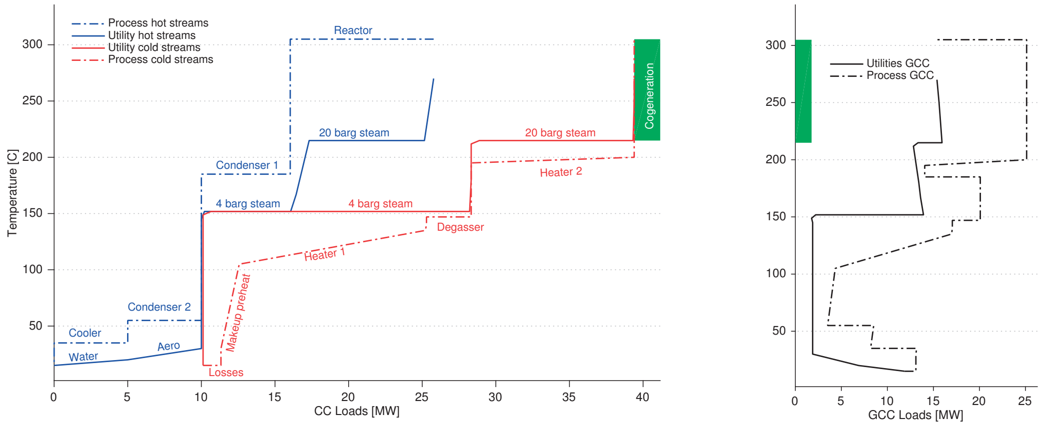
Table 5.2 – Thermal properties of streams in Total Site Analysis example.

| Process Name | Utility | Flowrate | $\Delta T/2$ [°C] | $T_{Util}$ [°C] | $T_{Proc,in}$ [°C] | $T_{Proc,out}$ [°C] |
|---|---|---|---|---|---|---|
| Reactor | 20 barg steam | 15 t/h | 15 | 270 | 320 | 320 |
| Condenser 1 | 4 barg steam | 20 t/h | 15 | 167 | 200 | 200 |
| Condenser 2 | Aero-cooling | 5 MW | 25 | | 80 | 80 |
| Cooler | Water-cooling | 5 MW | 15 | | 50 | 50 |
| Heater 2 | 20 barg steam | 20 t/h | 15 | 250 | 180 | 185 |
| Heater 1 | 4 barg steam | 20 t/h | 15 | 180 | 110 | 130 |
| Degasser (injection) | 4 barg steam | 5 t/h | 0 | 180 | 135 | 135 |
| Makeup preheat | 4 barg steam | 3 t/h | 15 | 180 | 15 | 125 |
| Losses | 4 barg steam | 2 t/h | 0 | 180 | 15 | 15 |
| Turbine | 90 barg steam | 25 t/h | | 450 | | |

The above proposed methodology was applied to the consumers and producers of Table 5.2 to obtain the temperature-enthalpy profiles of the utility consumers and producers. These were input into the LuaOSMOSE software [59] resulting in the corrected temperature CCs and GCCs shown in Figure 5.12. The contributions of the streams are named on the graph. The cogenerated power is shown in green. The pinch point of the system is 55°C.

Figure 5.13 shows some key results of the analysis. In the lefthand graph, we see that the $MER_H$ is of 11.9 MW compared to 13.6 MW steam consumption. 1.8 MW are extracted by the turbine bringing the total boiler supply to 15.4 MW.

15.7 MW of heat are recovered in the Reactor and Condenser 1. The losses are shown in red stripes, amounting to 1.2 MW.




(a) CCs (b) GCCs

Figure 5.12 – Composite Curves (a) and Grand Composite Curves (b) for Total Site Analysis.

The righthand graph of Figure 5.13 shows the site cooling requirements, with an $MER_C$ of 8.4 MW compared to the 10.0 MW of utility cooling by the aero and water-cooling.

The difference between the MER and the utility consumption is the heat exchange penalty of the system, caused by streams exchanging across the pinch point. It is equal to 1.6 MW and is due to the losses and heating of the makeup water by steam.

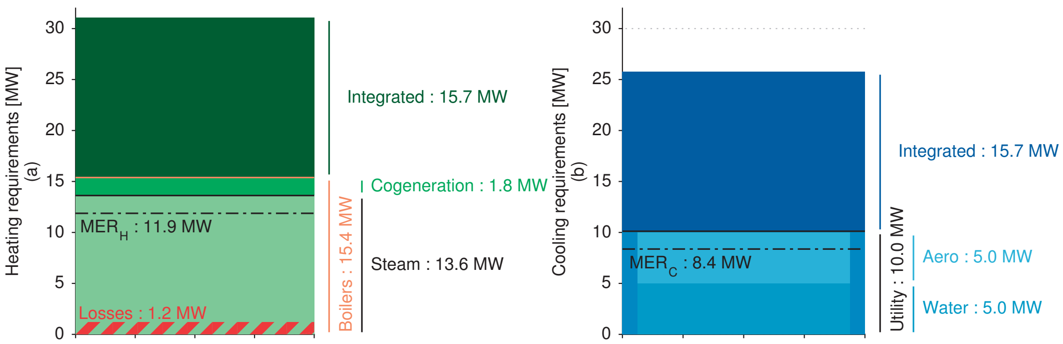



Figure 5.13 – Key properties of Total Site heating (a) and cooling requirements (b).

Further study is now possible to establish energy efficiency solutions, for example through the use of a heat pump between 170 and 200°C or through increased cogeneration by reducing the 20 barg pressure level.

## 5.3 Application to Typical Industrial Cluster

The above defined methodology was applied to the streams of the TIC. A brief description of the data and assumptions of the TSA can be found in Sections 5.3.1 and 5.3.2.

The TSA results of Site R and P are presented in Sections 5.3.3 and 5.3.4 followed by their combined analysis in Section 5.3.5. Some modifications are proposed to the existing utilities in Section 5.4 to improve the overall energy performance.

### 5.3.1 Data of Total Site Analysis

In total 159 streams and 13 steam turbines were identified in Site R and P with details given in Table 5.3. The TSA presented below is a multi-period study, using the periods defined in Table 4.1. Further details concerning the process requirements and streams can be found in Appendix A and [53].

Each stream was defined twice (for the process and utility streams) using TBP definitions were used for all streams. In total 2162 data points were considered for each of the 19 periods. Steam turbines were defined only according to mechanical power production.

Table 5.3 – Heat exchange streams used for Total Site Analysis.

| | Site R | Site P |
|---|---|---|
| Steam generation (hot process) | 11 | 4 |
| Steam consumption (cold process) | 17 | 22 |
| Tracing | 9 | 6 |
| Stripping | 9 | 4 |
| Losses | 14 | 2 |
| Aero-cooling | 14 | 15 |
| Cooling water | 16 | 13 |
| Turbines | 7 | 9 |
| Total streams | 97 | 75 |

All streams were defined by their process and utility requirements using the dual representation. The utility flowrates were used to define the energy loads for all cases except the aero-cooling, where some process modelling was required. All process temperatures were defined using TBPs, with the exception of the steam stripping. These were defined using the pressures of their receiving columns. As the water preparation and degassing requirements of both sites are known, the overall values were used rather than detailing them for each stream.

When the isentropic efficiency of a turbine was unknown, it was assumed to be $\eta = 30\%$.

As seen in Chapter 2, losses are present in Site R's utility network and PUs, whereas they are only present in Site P's utility network.

### 5.3.2 Assumptions of Total Site Analysis

Table 5.4 shows the key assumptions used for the modelling of the process requirements in the TSA, namely the approach temperature $\Delta T/2$ and the calculations used for process temperature-enthalpy definitions.

Table 5.4 – Key assumptions for processes in Total Site Analysis.

| | $\Delta T/2$ [°C] | $T$ [°C] |
|---|---|---|
| Cold process | 10 | TBP |
| Hot process | 10 | TBP |
| Stripping | 0 | $T_{sat,p^*}$ with $p = p_{Column} + 0.5$ barg |
| Hello Tracing | 10 | TBP |
| Losses | 0 | $T_{in} = 25$, $T_{out} = 25$ |

Table 5.5 shows the key assumptions for the utility definitions. When measures were absent, the superheating temperature of steam $T_{Sup}$ was assumed to be 15 °C above $T_{Sat}$. A HWN is defined though it is not existent in the current TIC (it figures in the improvement scenarios). Its $T_{hot}$ is that of the demineralised water to be easily scalable in the case of increased or decreased demand.

Table 5.5 – Key assumptions for utilities in Total Site Analysis.

| | $\Delta T/2$ [°C] | $T_{cold}$ [°C] | $T_{hot}$ [°C] |
|---|---|---|---|
| Steam | 10 | $T_{Des} = T_{Sat} - 3$ | $T_{Sup} = T_{Sat} + 15$ or measure. |
| HWN | 10 | 100 | 145 |
| Aero-cooling | 20 | 15 | 25 |
| Cooling Water | 10 | 8 | 13 |
| Demineralised water | | | 145 |

### 5.3.3 Site R Total Site Analysis results

As a first step in a TSA, it is best to properly understand process demand as it defines the utility requirements. A Pinch Analysis was therefore carried out on the process data. Figure 5.14 shows the pinch point of Site R for the different periods, which lies between 70°C and 130°C.

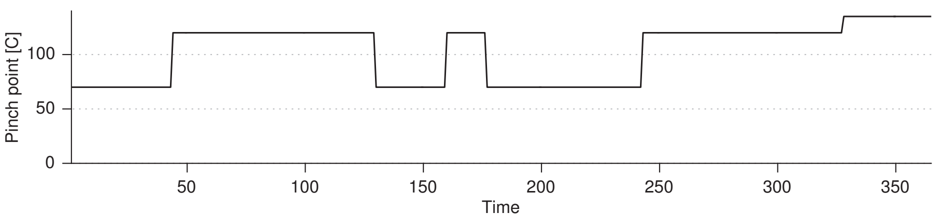
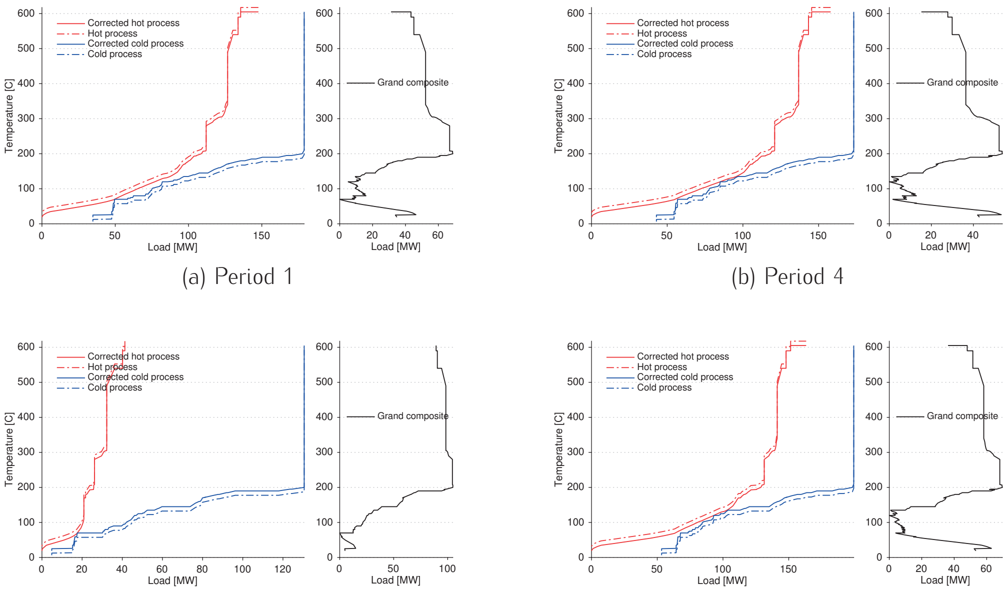



Figure 5.14 – Site R pinch point.




(a) Period 1 (b) Period 4 (c) Period 6 (d) Period 18

Figure 5.15 – Pinch Analysis of Site R for periods 1 (a), 4 (b), 6 (c) and 18 (d).

Figure 5.15 shows the CCs and GCCs for Site R's process for four periods, chosen due to their different pinch points. Period 6 was specially chosen for having the highest $MER_H$.

The CCs show that between 70°C and 130°C, heat transfer is complicated as the process streams are almost parallel to one another. This means that little can be recovered in the form of steam in these temperature ranges, a HWN being more suitable. The cold process curves indicate that a significant quantity of steam could be used at a lower pressure than the existing 5 barg steam.

Several PUs are shut down during period 6, which explains why its curves are so different from those of the others. The cooling requirements are significantly decreased during this period to 4.9 MW. Though the sink and source profiles are generally similar in appearance, the GCCs reveal the differences more clearly, as self sufficient pockets open and close depending on process stream varitions. Temperature differences between the near pinch points and pinch points remain small.

These CC and GCCs highlight that the thermal exchanges of Site R must be considered using a multi-period approach as the key properties of the system change significantly with time. The mean $MER_H$ is 35.5 MW with a peak at 89.3 MW in period 6. The mean $MER_C$ is 38.9 MW with a less imposing peak value of 53.3 MW in period 17.

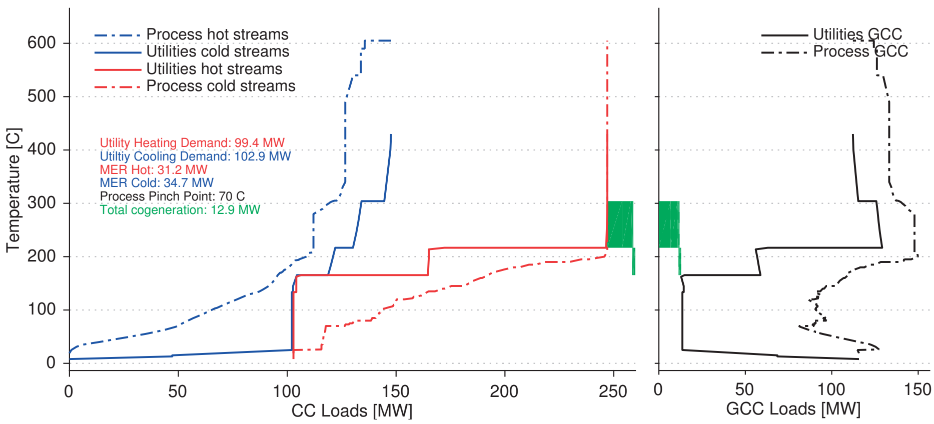



Figure 5.16 – CCs and GCCs of Site R for period 1.

Figure 5.16 shows the TSA results for period 1 of Site R. A schematic representation of the cogeneration is given in green. The dotted blue curves show the corrected process heat sources and the solid show their corresponding utilities. Below 170°C all cooling takes place using aero or water-cooling. Steam is generated at 2 barg, 5 barg, 20 barg and 90 barg, as can be seen in the blue plateaus.

The dotted red curve shows the process heat sinks while the solid red line shows the hot utilities. Steam is consumed at 2 barg, 5 barg and 20 barg. No direct 90 barg steam consumption takes place, as it is only used for cogeneration purposes. The leftmost plateau of the dotted red curves corresponds to the steam leaks and condensation losses of the system.

The GCCs highlight the significant difference between the consumption of utility cooling and heating compared to the minimum energy requirements. In effect, the $MER_H$ of the system is equal to 31.2 MW for period 1, compared to a total utility heating of 99.4 MW. The $MER_C$ is equal to 34.7 MW compared to the supplied 102.9 MW.

Figure 5.17 shows the key thermodynamic properties of Site R throughout the different periods on the left and their average values on the right. The $MER_H$ and $MER_C$ are shown in dotted black lines .

The boilers supply 950.4 GWh/yr to meet the overall heating demand of 1218.7 GWh/yr. 7.7% of this energy is converted to mechanical power and 8.6% is lost in the form of steam leaks and condensation.

Steam generated through process cooling delivers a mean 42.3 MW of steam to processes, representing on average 25.9% of the overall heating requirements of Site R. Its peak value is 47.7 MW, during period 15. The mean steam demand is 96.8 MW with a peak 113.0 MW, also during period 15.

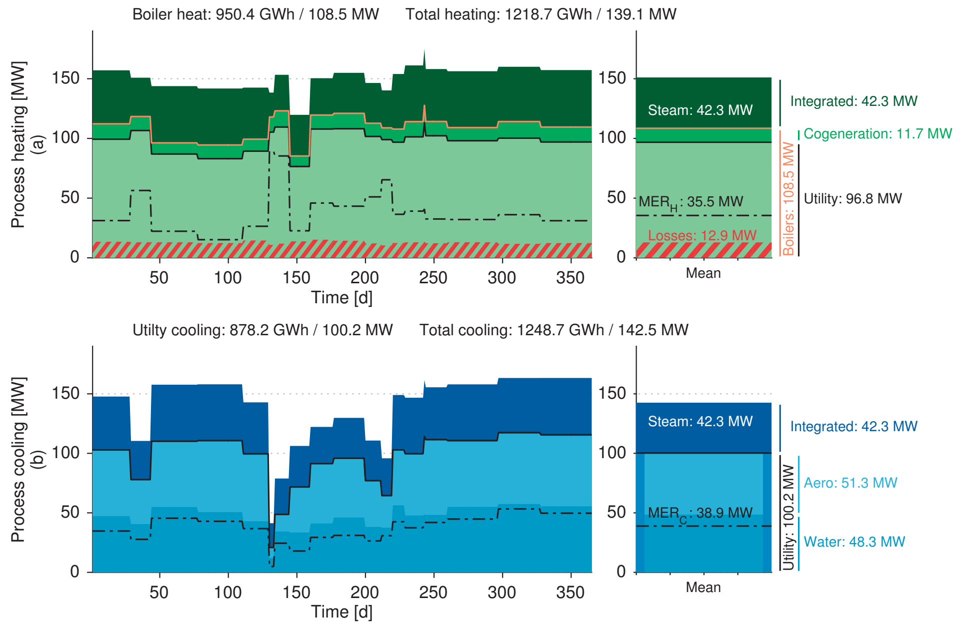



Figure 5.17 – Key heating (a) and cooling (b) properties of Site R.

The utility cooling requirements collapse from period 6 to 12 as a result of PU D being offline. A total 878.2 GWh/yr is evacuated from the system, 51% through aero-cooling and 49% through water-cooling.

### 5.3.4 Site P Total Site Analysis results

The pinch point of Site P is at 105°C for all periods except 12 where it rises to 120°C. Figure 5.18 shows the CCs and GCCs for Site P's process for four periods, chosen due to their varied demand in heating and cooling.

The CCs remain very similar in appearance throughout the different periods, despite their varied overall loads. The mean $MER_H$ is 18.3 MW with a peak value at 62.5 MW. The $MER_C$ is more consequent, with a mean value of 143.8 MW and a peak at 160.5 MW. The dominance of the cooling requirements reflects the exothermic nature of petrochemical processes.

Figure 5.19 shows the TSA results for period 1 of Site P. Steam is produced at 90 barg, 30 barg and 5 barg and 2 barg. It is consumed at 2 barg, 5 barg and 30 barg. As in Site R, 90 barg is only used for cogeneration.

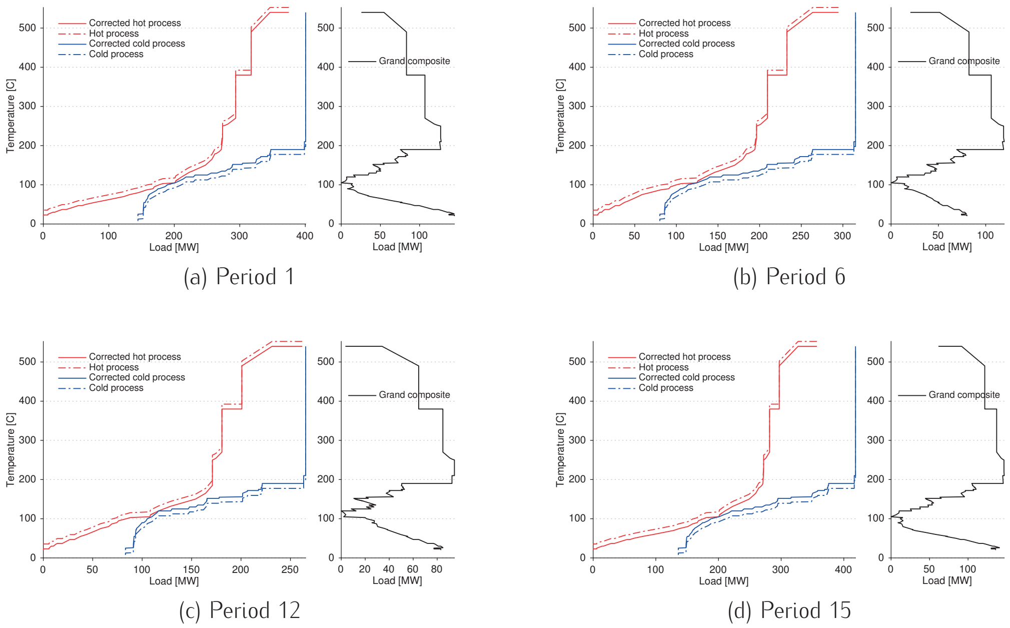



Figure 5.18 – Pinch Analysis of Site P for periods 1 (a), 6 (b), 12 (c) and 15 (d).

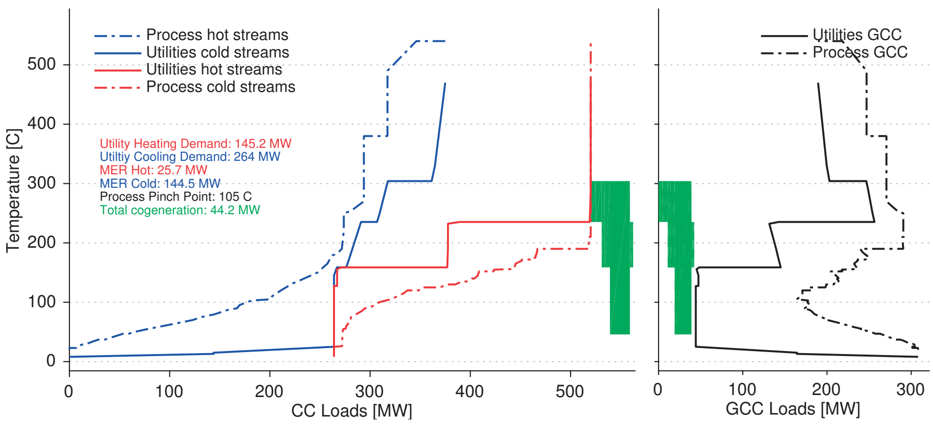



Figure 5.19 – CCs and GCCs of Site P for period 1.

Figure 5.20 shows the key thermodynamic properties of Site P throughout the different periods. The overall energy requirements from the boilers are of 1523.3 GWh/yr to meet the overall heating demand of 2044.8 GWh/yr. 15.8% of this energy is converted to mechanical power through cogeneration and 3.0% is lost in the form of steam leaks and condensation (mean losses are 8.3 MW). The mean steam demand is 130.1 MW with a peak 192.2 MW in period 15.

Steam generated through process cooling delivers a mean 103.4 MW of steam to processes representing on average 44.3% of the overall heating requirements of Site P. Its peak value is 123.5 MW, also during period 15.

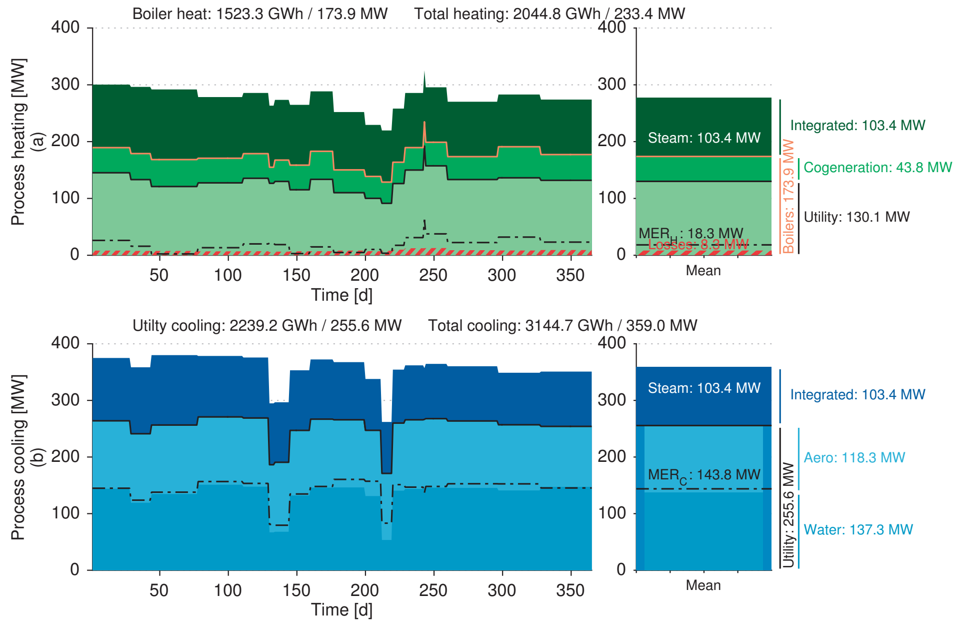



Figure 5.20 – Key heating (a) and cooling (b) properties of Site P.

The utility cooling requirements are significantly reduced in periods 6,7 and 12 as a result of reduced cooling water demand from PU A. A total 2239.2 GWh/yr is evacuated from the system, 46.7% through aero-cooling and 53.3% through water-cooling.

As in Site R, generation of low pressure steam is complicated in Site P, as the heat sources have few plateau's between 100 and 200 °C.

### 5.3.5 Typical Industrial Cluster Total Site Analysis results

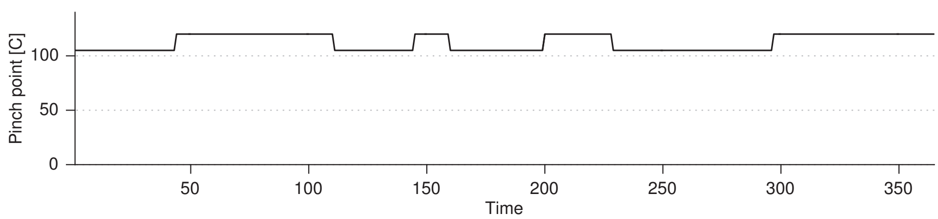
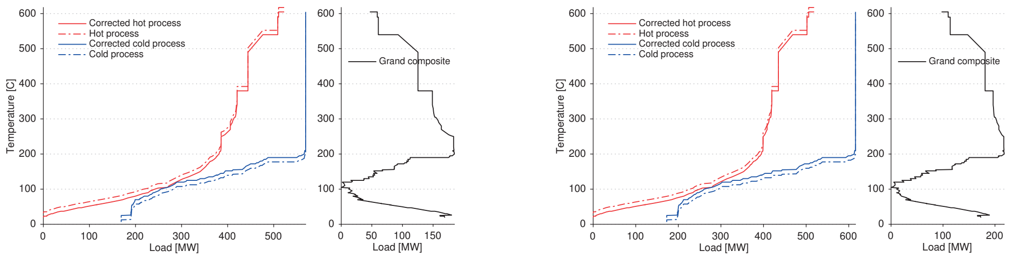



Figure 5.21 – Typical Industrial Cluster pinch point.

A TSA was made using all streams from Site's R and P to identify the process and utility requirements of the entire TIC. The pinch point of the TIC varies between 105°C and 120°C, seen in Figure 5.21. The CCs and GCCs are shown in Figure 5.22 for periods 1 and 15. The curves are




(a) Period 1 (b) Period 15

Figure 5.22 – Pinch Analysis of Typical Industrial Cluster for periods 1 (a) and 15 (b).

very similar in appearance, with a highly bottlenecked zone between 100°C and 130°C, which explains the variations in pinch points as near pinch points become activated due to changing operating conditions.

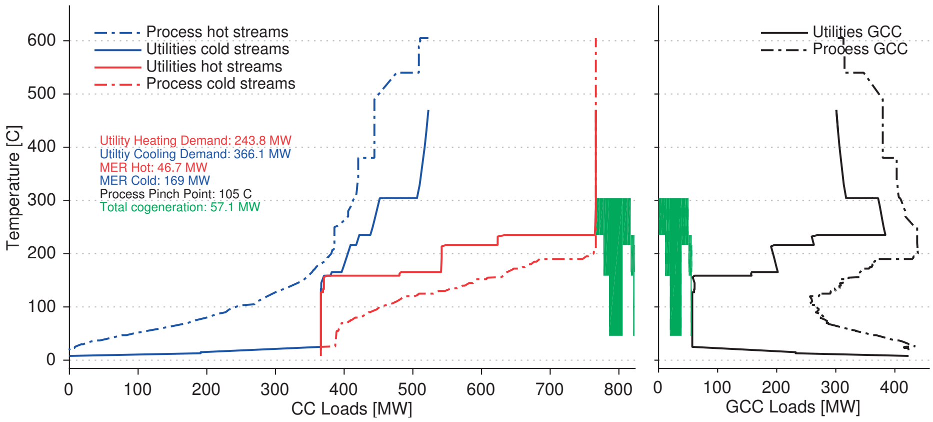



Figure 5.23 – CCs and GCCs of Typical Industrial Cluster for period 1.

Figure 5.23 shows the TSA results for the TIC for period 1 while Figure 5.24 shows an overview of the key thermodynamic results for all periods. Table 5.6 shows a comparison of some key results of the TSAs of Sites R and P and the overall Cluster.

Table 5.6 – Key Total Site Analysis results for Typical Industrial Cluster and individual sites.

| | Cogeneration [MW] | | Heating [MW] | | $MER_H$ [MW] | | Cooling [MW] | | $MER_C$ [MW] | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Mean | Max | Mean | Max | Mean | Max | Mean | Max | Mean | Max |
| Site R | 11.7 | 14.7 | 96.8 | 113.0 | 35.5 | 89.3 | 100.2 | 117.4 | 38.9 | 53.3 |
| Site P | 43.8 | 54.7 | 130.1 | 192.2 | 18.3 | 62.5 | 255.6 | 270.8 | 143.8 | 160.5 |
| Cluster | 56.4 | 69.3 | 220.5 | 298.3 | 37.0 | 73.5 | 355.2 | 381.0 | 171.7 | 196.0 |

The following can be said about the TIC's heating and cooling demand:

- As was expected, the $MER_H$ of the TIC is smaller than that of the combined sites, as further heat recovery opportunities appear. The same is true for the $MER_C$.

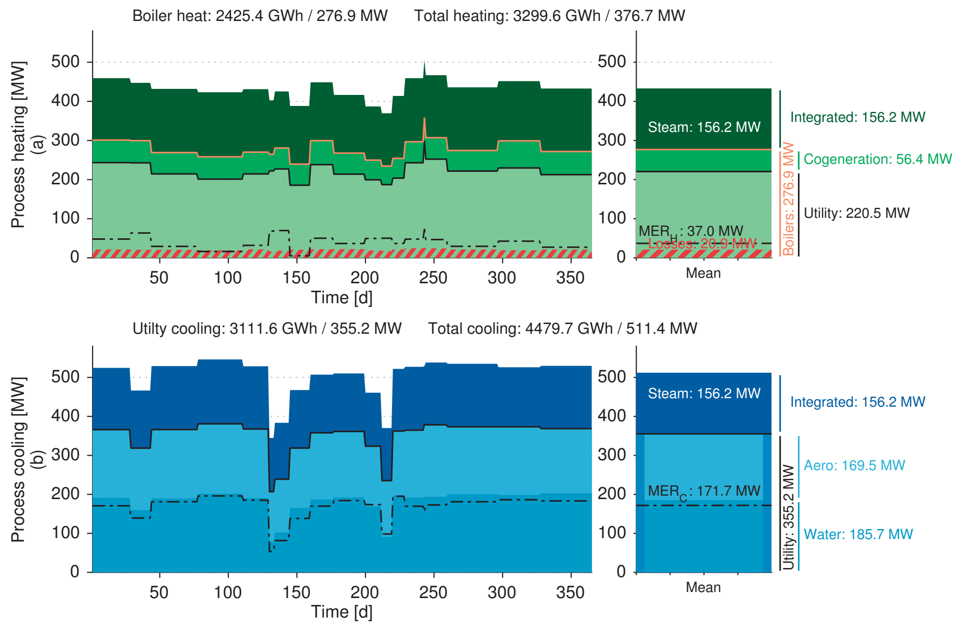



Figure 5.24 – Key thermodynamic properties of the Typical Industrial Cluster.

- The peak $MER_H$ (73.5 MW) occurs when demand is highest in period 15, though high values are also present in periods 6 and 7 as a result of Site R's PU D shutdown.
- Despite Site P's $MER_H$ being half that of Site R's, its steam demand is 34% higher.
- The TIC steam demand is quite stable with a mean value of 220.5 MW and a peak 298.3 MW.
- The TIC cooling demand varies between 206.9 and 381.0 MW with a mean value of 355.2 MW. The major variations are caused by reductions in cooling water demand from Site P's PU A and Site R's PU D shutdown.
- Cogenerated power is responsible for 19.7% of the overall energy consumption.
- Significant amounts of exergy are destroyed by cooling hot process streams with aero and water-cooling, with many penalising exchanges.
- 5 barg steam is used to heat many streams below the pinch point, thereby increasing the penalty.
- 5.7% of all generated steam is lost in the form of steam leaks or condensation, also causing an increase of the penalty.
- Increased heat recovery in the form of steam would be complicated given the shape of the hot process curves. They are more suited to recovery through a hot water or oil network.

## 5.4 Typical Industrial Cluster retrofit

Any heat source transferring heat below the pinch point is penalising (between 105 and 120°C for the TIC). This means that many of the 5 barg steam consumers are penalising, as are most water and aero coolers.

As mentioned above, given the profiles of the CCs, recovering additional heat in the form of steam is complicated as few plateaus are present at low temperatures in the hot processes. However, given the slope of the curves, a HWN is feasible. Retrofit solutions therefore mainly focus on a HWN with the following properties:

1. Water pressurised above 3 barg.
2. Heated and cooled between $T_{Cold} = 100$ and $T_{Hot} = 145$°C.
3. In the case of demand, demineralised water ($T_{Demin} = 145$°C) can be used to supply additional water, tough this can also be achieved through a heat exchange with steam in a kettle.
4. In the case of surplus, aero or water coolers can be used to cool down the network.
5. The thermal capacity of water is assumed to be constant at $c_p = 4.25 \frac{kJ}{kg \cdot K}$ for the given temperature range.

To facilitate financial calculations around a retrofit solution, care was taken to make sure that all heat sinks be in Site P, while 6 of the 8 sources are in Site R. In this way the entirety of the works can be billed to Site P. In an effort to balance the supply and demand of heat, the heat exchangers to be modified were chosen so as to have approximately equal average heat loads.

7 aero coolers and 1 water cooler were identified as partially or entirely penalising, shown in Figure 5.25. Dotted lines represent corrected temperatures while solid lines show the process temperatures. Certain streams could be used entirely (for example S1C AERO 2), while others had to be separated into two heat exchanges (S1A AERO 3) with the remaining heat to be evacuated as before. Given the temperature ranges of water cooler S1C CW 3 it is possible to produce 5 barg steam and hot water with it, though only the HWN is used.

Though numerous penalising heat consumptions were identified on the cold process side, only 7 were chosen to be included in the HWN. These exchangers currently use 5 barg steam to heat process streams, generally below the pinch point. Their consumption of steam is replaced by hot water for the retrofit investigation.

Details about the loads of the identified heat sources and sinks are given in Table 5.7. Most heat sources come from Site R, and all heat sinks are in Site P. The table shows that while the mean loads of the sources and sinks are well matched, it is likely that balancing issues may occur as the peak loads are not the same.

A steam consuming kettle can be used to generate more hot water when demand surpasses supply and an aero cooler can evacuated excess heat from the HWN when it is present.

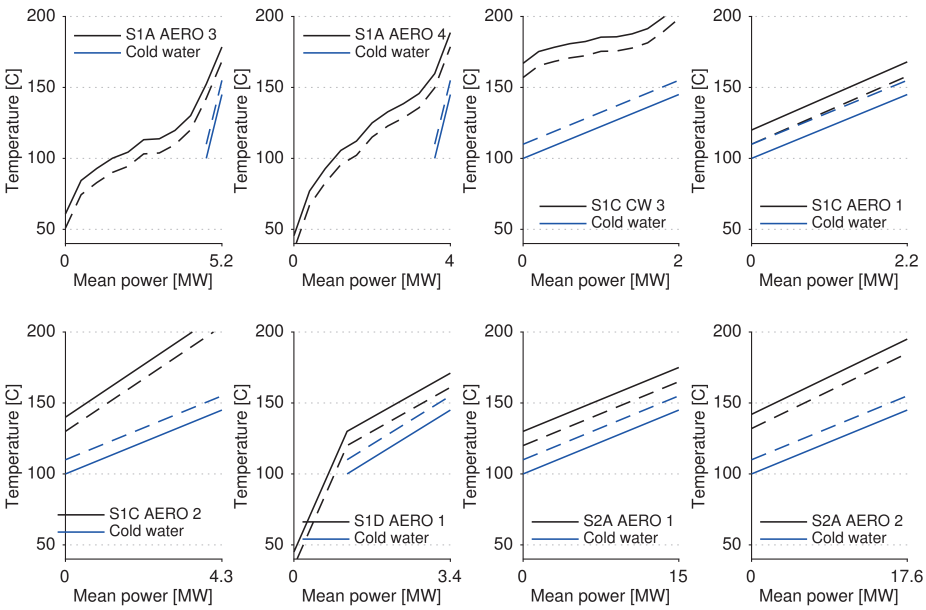



Figure 5.25 – Temperature-power profiles of modified heat sources.

Table 5.7 – Proposed TIC retrofit modifications overview.

| Site | PU | HEX | Type | Proposed | Mean load [MW] | Max load [MW] |
|---|---|---|---|---|---|---|
| R | A | AERO3 Split | Aero cooling | HWN prod. | 1.0 | 1.5 |
| R | A | AERO4 Split | Aero cooling | HWN prod. | 0.8 | 1.2 |
| R | A | CW3 | Cooling water | HWN prod. | 3.2 | 4.9 |
| R | C | AERO1 | Aero cooling | HWN prod. | 2.2 | 3.4 |
| R | C | AERO2 | Aero cooling | HWN prod. | 4.3 | 6.5 |
| R | D | AERO1 Split | Aero cooling | HWN prod. | 1.2 | 3.0 |
| P | A | AERO1 | Aero cooling | HWN prod. | 15.0 | 16.4 |
| P | A | AERO2 | Aero cooling | HWN prod. | 17.6 | 19.2 |
| | | Total | | HWN prod. | 45.4 | 52.8 |
| P | B | VBP HEX Cons1 | Steam cons. | HWN cons. | 2.2 | 2.6 |
| P | B | VBP HEX Cons2 | Steam cons. | HWN cons. | 0.8 | 0.9 |
| P | E | BP HEX Cons1 | Steam cons. | HWN cons. | 1.5 | 1.8 |
| P | E | BP HEX Cons2 | Steam cons. | HWN cons. | 6.4 | 26.1 |
| P | U | BP Site Tracing | Steam cons. | HWN cons. | 20.9 | 43.5 |
| P | U1 | BP Site Tracing2 | Steam cons. | HWN cons. | 8.7 | 13.1 |
| P | U | Air Preheat | Steam cons. | HWN cons. | 4.5 | 10.3 |
| | | Total | | HWN cons. | 45.0 | 74.4 |

The TSA was carried out with these modifications. Figure 5.26 shows the resulting CCs and GCC for period 1. The water network can clearly be seen with its sloped curves between 100 and 145°C. In period 1, the consumption of hot water surpasses the generation by the hot sources.

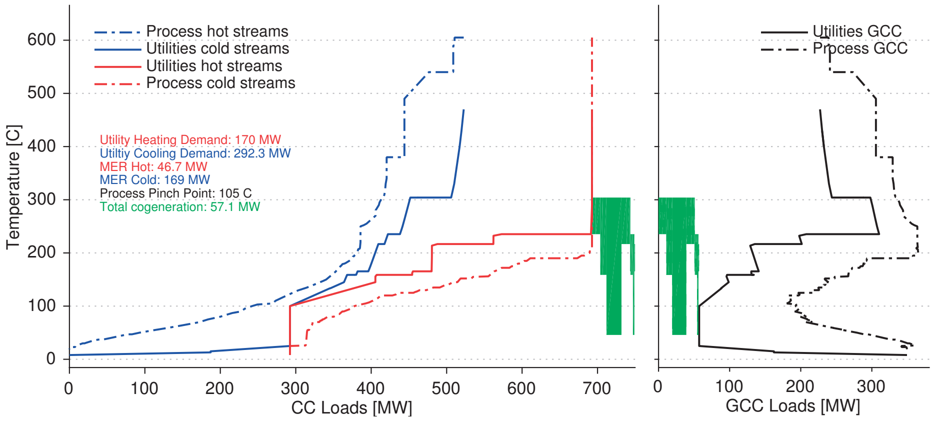



Figure 5.26 – CCs and GCCs of modified Typical Industrial Cluster for period 1.

Figure 5.27 shows the overview of the key thermodynamic results through time. The heat recovery of the water network is shown in white. Table 5.8 compares the key TSA results of the TIC before and after retrofit. The benefits of the HWN can clearly be seen, leading to an overall steam consumption reduction of 18.8% (boiler load reduction of 15.0%).

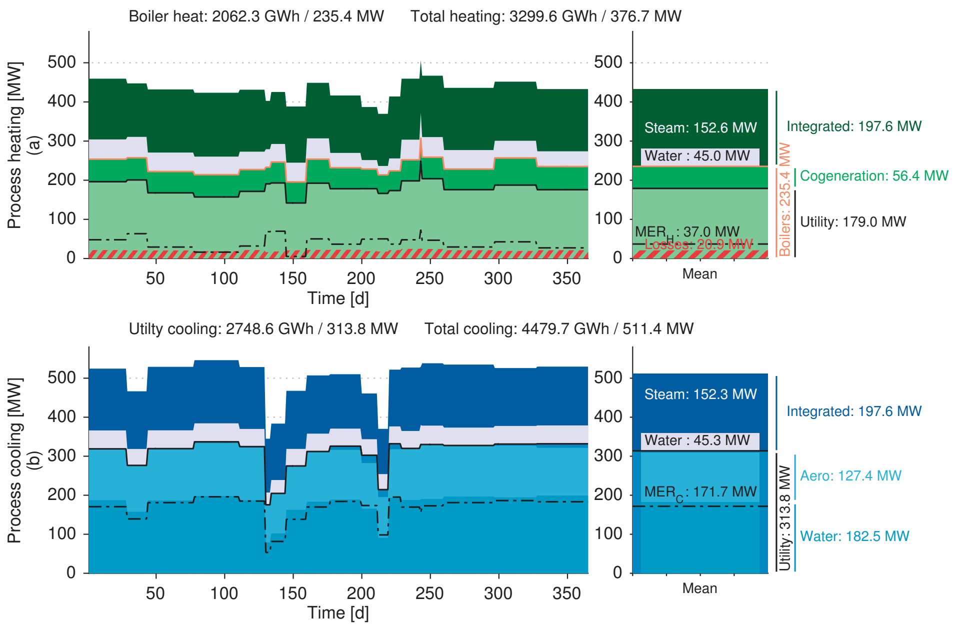



Figure 5.27 – Key thermodynamic properties of retrofitted Typical Industrial Cluster.

A mean 45.0 MW of hot water are used to heat processes, compared to a mean generation of 45.3 MW. The -0.3 MW difference is matched through a kettle. Figure 5.28 shows the generation (in red) and consumption of hot water (in blue).

Table 5.8 – Comparison of key Total Site Analysis results for Typical Industrial Cluster before and after retrofit.

| | Cogeneration [MW] | | Heating [MW] | | $MER_H$ [MW] | | Cooling [MW] | | $MER_C$ [MW] | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Mean | Max | Mean | Max | Mean | Max | Mean | Max | Mean | Max |
| Cluster | 56.4 | 69.3 | 220.5 | 298.3 | 37.0 | 73.5 | 355.2 | 381.0 | 171.7 | 196.0 |
| Retrofitted Cluster | 56.4 | 69.3 | 179.0 | 248.6 | 37.0 | 73.5 | 313.8 | 337.0 | 171.7 | 196.0 |
| Difference | 0% | | -18.8% | | -0.0% | | -11.7% | | -0.0% | |

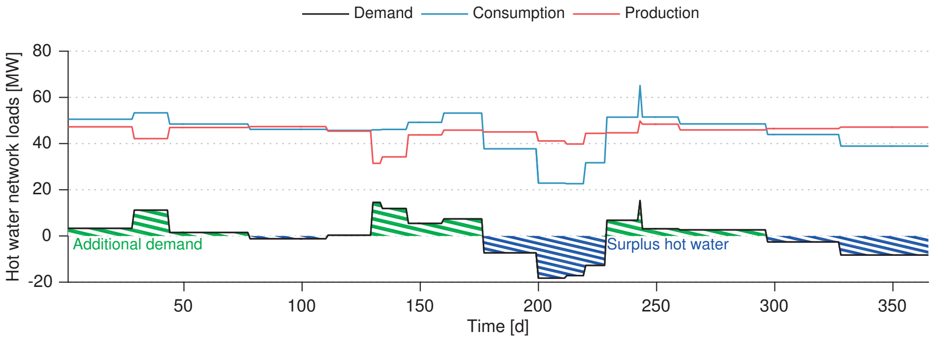



Figure 5.28 – Demand for additional hot water in Hot Water Network.

The black curve represents the difference between the consumption and generation of hot water, which corresponds to the demand for additional hot water generation. The areas shaded in green indicate that additional generation is needed, while those shaded in blue indiciate that the water network must be cooled as too much heat is available. When heat is evacuated through a cooling network, according to the more in more out principle, heat is wasted, this should therefore be minimised.

The feasibility of the water network must be further analysed. Given the heat transfers, it is possible to calculate the required flowrate of water, which would be a mean 847.9 t/h with a peak value of 1225.6 t/h. This is nearly 50% more than the installed steam capacity of the TIC and would imply investments in water storage tanks and likely a secondary demineralisation plant.

The operational feasibility of such a HWN are discussed in Section 6.3.3. The following investments and work would be required to install the HWN:

- Installation of 8 hot water generators in lieu of existing aero and water coolers. Streams may still need to be further cooled once they exit the HWN heaters.
- Replacement of 7 steam heat exchangers with hot water exchangers in Site P.
- Installation of a kettle to produce surplus hot water when required.
- Installation of an aero cooler to cool HWN when excess heat is present.
- Installation of a water reservoir to feed and draw from to meet demand.
- Installation of site wide piping for the HWN.

- Installation of a control system for the HWN.

## 5.5 Industrial results

The results proposed above reflect the reality of the chemical industry, with a pinch point typically between 100°C and 150°C. Experience has shown that the pinch point is usually below the saturation temperature of the low pressure steam header. Heat sinks around these temperature ranges are typically supplied by low pressure steam (3.5 - 5 barg). Heat sources around the pinch point are generally cooled through aero or water coolers. The following types of heat exchanges have therefore been identified as creating penalties or providing 'easy' integration opportunities.

- Tank and pipe tracing at low temperatures using steam. Using steam to heat below the pinch point creates a penalty as the steam is generated above the pinch. As such, tank and pipe tracing should use lower temperature heat sources where available.
- Demineralised water pre-heating. The temperature of demineralised water is that of the saturation temperature of the low pressure steam. Therefore most of the heat exchanged to heat the raw water from its source temperature to its target is likely to be penalising. Making use of heat below the pinch point can reduce this penalty significantly.
- Air pre-heating. Steam is often used to pre-heat the air before combustion in boilers, from atmospheric temperature to as much as 200°C. Steam used to heat the air below the pinch point is entirely penalising and should therefore be replaced with another source of heat.
- Steam leaks. Plugging any steam leaks logically leads to reduced energy demand.
- Water or aero-cooling of process streams with temperatures above the pinch point. Heat evacuated to the atmosphere from above the pinch point creates a penalty equivalent to the entirety of the load. Through integration, this heat can be used to heat a process above the pinch point.
- Water or aero-cooling of process streams with temperatures below the pinch point. Though such heat exchanges are not penalising, they still offer the possibility of reducing the energy bill. Such heat could for example be used to pre-heat water or air.

## 5.6 Conclusion

As industrial clusters can be complex, with hundreds or thousands of heat sources and sinks, a systematic methodology was required to simplify the tasks of data collection and modelling of the process and utility streams in view of carrying out a TSA.

A list of data to collect and some typical temperature-enthalpy representations of the heat sources and sinks of refining and petrochemical sites were proposed to accomplish this task. Using a dual representation of process streams by their thermal and utility requirements, it was possible to further simplify data collection and ensure that mass and energy balances of the system were respected. In this way, aero-cooling, water-cooling, steam and a Hot Water Network (HWN) were taken into consideration.

By including the demineralisation and degassing requirements of the steam generation into the TSA, overall energy requirements of the utility networks of an industrial site or cluster were established.

The method was demonstrated on the Typical Industrial Cluster case study, using the reconciled data from Chapter 3 and the multi-period definitions from Chapter 4. Thanks to the proposed formulations, it was possible to carry out a complex multi-period TSA including 159 utility and therefore process streams, each defined by TBP and 8 independent steam pressure levels over 19 periods, totalling in $41.1 \times 10^3$ data points.

The results found that the 225.5 MW of heat is supplied to the cluster, rather than its theoretical $MER_H$ of 37 MW, with the highest demand from Site P. As the pinch point varied between 105°C and 120°C, the difference between the utility supply and $MER_H$ can mostly be explained by the presence of losses, tracing requirements of the TIC and low temperature heating using 5 barg steam. The very low $MER_H$ in comparison to utility bill highlights the potential for heat integration symbiosis in the TIC.

A HWN was proposed as an energy efficiency solution with the potential to reduce overall heating demand of the cluster by 18.8% and overall cooling demand by 11.7%. This HWN would use heat available from aero and water-coolers in Sites R and P to supply low temperature heat exchangers and tracing in Site P.

The results also highlighted that a mean 20.9 MW of the 367.7 MW of heat demand is lost in the form of steam leaks and condensation losses. Though the values of the losses are comparatively small, their absolute costs figure in the millions of dollars per year.

The multi-period study revealed that Site R and Site P cannot be considered as stable systems, as their key thermodynamic properties change with time. Despite the HWN heat sources and sinks being well matched when using yearly mean values, significant imbalances were present, requiring additional investment in a hot water kettle to supply heat to the HWN on multiple occasions. Given these findings, it is recommended to perform further analysis and evaluate the economic and operational feasibility of the HWN.

The case study would have strongly benefited from using mathematical optimisation formulations, which may have permitted the identification of further cogeneration potential or the installation of heat pumps and lower pressure steam levels. Optimising the HWN's sources and sinks would surely have reduced its requirement for a hot water kettle.

This work has shown that TSAs are an effective way to identify Energy Integration solutions industrial clusters, strongly benefiting from a multi-period approach to increase process knowledge and identify sizing issues of proposed solutions.

An aspect of TSAs which has yet to be addressed concerns the operations of the concerned utility networks. As TSAs do not take into consideration the transport of heat transfer fluids in their networks (for example steam going through letdowns and turbines), no clear picture is painted about the operability of said networks. Therefore, TSA solutions remain complicated to communicate to decision makers likely to invest in their potentially great benefits.

# 6 Optimal operations and resilient investments in steam networks

*This chapter provides a methodology to optimise the operations of a steam network despite low boiler availability as well as a simulation algorithm to establish the resilience of utility networks in the face of disturbances such as equipment failures.*

## 6.1 Introduction

As was discussed in the previous chapters, the uses of steam in industrial sites are multiple. These include process heating in heat exchangers, for steam stripping, generation of mechanical power through turbines. It can also be generated while cooling high temperature processes.

In industrial clusters, steam is mostly produced in centralised boilerhouses at high pressure and dispatched into the steam network. It is consumed at different pressure levels depending on the process requirements. Steam that is not consumed at high pressure is letdown to the lower pressure headers either through steam turbines or letdowns, which can be coupled to desuperheaters.

While letdowns cannot produce valuable mechanical work like turbines, their desuperheaters can be useful when operating reserves are low (when demand reaches steam generation capacity). Desuperheaters inject demineralised water into hot steam to cool it, thereby increasing the overall quantity of steam.

In a well regulated steam network, the lowest pressure header should consume all available low pressure steam. Any excess low pressure steam must be eliminated through condensing turbines or atmospheric discharges. The latter has the result of releasing precious demineralised water to the atmosphere as well as wasting the heat of steam.

Steam demand is defined as the difference between steam consumption and production by Process Units (PUs). It corresponds to the steam that must be generated by the steam boilers for the network to be operable. An optimised steam network should aim to:

- Supply steam to meet demand at all pressure levels.
- Minimise steam production costs.
- Maximise the use of cogeneration turbines.
- Minimise atmospheric discharge of low pressure steam.
- Optimally activate letdowns and their desuperheaters when operating reserves are low.

Though these rules are simple, large steam networks may be complicated to operate given the multiple pressure levels and numerous equipments which simultaneously produce and consume varying amounts of steam at different pressure levels. The causes for steam demand variation explained in the introduction of Chapter 5 also apply here.

Total Site Analysis (TSA) studies reveal important information about thermal power of steam and utility networks. However, the transport of steam across pressure levels (by letdowns and turbines) is not taken into consideration, therefore it does not give a complete picture about the operability of the steam network.

Calculating the optimal costs of a steam network and the pathways of the steam is an important step towards better understanding such complex systems as well as targeting reduced fuel consumption and costs. Furthermore, as energy integration solutions identified in a TSA must often be backed up by steam and cooling supply to deal with additional demand or excesses in heat, it is important to understand their operability and economic impacts in order to prove their feasibility and communicate results.

The steam generation capacity of an industrial site is usually oversized to deal with high demands in steam; however, combinations of events can lead to operating reserves falling to zero as demand surpasses the available generation capacity (undercapacity). This can for example happen when a boiler is offline at the same time as high demand.

Boiler shutdowns may be due to maintenance operations or failures. While maintenance operations are typically planned and organised to limit disruptions, boiler failures are unplanned. These can be caused by overheating, thermal stress and mechanical fatigue [89].

When undercapacity events occur, the letdown desuperheaters can help reduce their impacts, though load shedding may be required. This implies partially or completely shutting down PUs to reduce or eliminate their steam demand. PU shutdowns can incur significant lost profits, complicated startups and even dammage to key equipments [91].

In order to avoid such events, steam networks must be designed to be resilient. Resilience is defined as the ability of a system to endure and minimise the impacts of perturbatory events, which can for example be meterological or technical in nature.

Steam networks are most vulnerable to high steam demand, extreme weather events (which influence steam demand) [40], boiler maintenance and boiler failures. While the impacts of the first three may be mitigated through proper planning, the boiler failures are unavoidable and cannot be planned.

A resilient steam network should always be able to supply its steam demand. This implies using a redundant number of oversized steam producing equipments to reduce the impact of maintenance operations and eventual boiler failures. Such a network must also be able to operate optimally when undercapacity events occur.

Steam networks are typically constructed in this way, with significant overcapacity and multiple steam boilers. Maintenance operations can therefore be planned with the knowledge that the steam network can still be fully operational. However, it is important to consider the impacts of a boiler failure while another is undergoing maintenance operations. Similarly, simultaneous boiler trips can have severe effects, especially when combined to high steam demand [91].

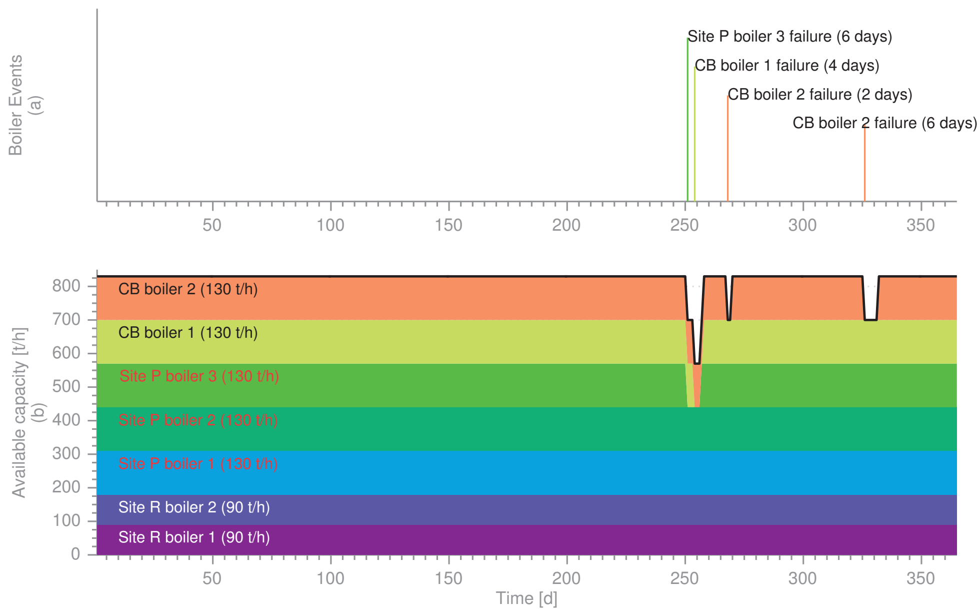



Figure 6.1 – Steam boiler failures (a) and remaining steam generation capacity (b).

Figure 6.1 illustrates the problem of multiple boiler failures applied to the Typical Industrial Cluster. The failures are randomly chosen based on the assumed failure rates of the boilers. In graph (a) four boiler failures can be seen to take place over a 365 day period. On day 251 Site P's boiler 3 goes offline for 6 days. On day 254, the CB boiler 1 does the same, for 4 days. The resulting overlap in boiler failures leads to a 32% reduction in steam generating capacity for the cluster, lasting 3 days. High steam demand during such a combination of events would lead to a collapse in operating reserves and therefore the need for load shedding.

While several works on steam networks have addressed optimal operations and investments, research on resilient operations and investments is lacking. This work addresses this gap by proposing a methodology to optimise steam network operations when facing undercapacity and to establish their resilience.

A literature review is proposed below, on the subject of resilience and optimisation of steam networks. As the topic has been explored in significant detail in the electricity networks, they are often used a comparison for the less researched steam networks.

### 6.1.1 State-of-the-art

Mixed Integer Linear Programming (MILP) has been used to optimise operations and investments in steam networks [93]. MILP uses mathematical optimisation to minimise an objective function $Obj$, to resolve equalities and inequalities, whose variables may be integers or continuous variables.

Steam consumptions on multiple headers, boiler houses, cogeneration turbines and condensate return can be optimised with respect to overall costs (including investments). This was extended to multiple periods to include PU ramp-up and ramp-down times when starting or shutting down [94].

Through the use of control systems, such mathematical formulations can be implemented in the steam networks of industrial sites to drive down steam production costs [92].

A setback of these works is the use of constant efficiencies, which was addressed through the use of part-load efficiencies for turbines and steam generating equipments [95]. The use of Mixed Integer Non-Linear Programming (MINLP) techniques also produced more accurate results [96], at the expense of higher computing power.

Undercapacity events occur when operating reserves fall to zero. In electricity networks, load shedding is one of the major responses to such events [98]. It prevents cascading black outs and equipment damage. In practice, this concept is often applied to steam network operations, though it has not been covered in the literature.

The above mentioned works on MILP [93, 94] establish the strict minimum investment size of steam generating equipments to meet steam demand under some very specific operational modes. In practise, this leaves no operating reserves for unusually high steam demand and excludes the possibility of carrying out maintenance operations on the steam generators. Choosing the right number of oversized equipments to offer redundancy in steam networks can be explored through case studies [91] though no formulations for its optimisation exist.

In electric networks, resiliency is chiefly achieved through redundancy in equipments and grid connections, diversity and evolvability of the networks [97]. Discrete event simulations can be used to establish the likelihood of network failures [101].

Boiler failures may not be very common but are inevitable in industrial sites [89]. Corrosion, mechanical and thermal stresses are the principle culprits for these failures. Given the unpredictable nature of these failures, scenario based studies are not sufficient to evaluate their impacts as the problem is highly combinatorial.

Network reliability concepts are commonly used in electricity networks, where 99.9% reliability rates are expected and achieved [100]. This corresponds to a maximum 9 hours of power shortages per year.

Loss of Load Probability was also defined [99] to express the amount of time undercapacity may be present in a network. The probabilities of generating a capacity level are compared to those of each load and its distribution function.

Some of these presented concepts can be used in steam networks, though their smaller scale and different operations may be challenging to bridge (for example due to complicated interactions between pressure levels). Establishing the resiliency of a steam network must include an analysis of the system's ability to overcome its key disturbances, namely high demand, boiler maintenance and boiler failures. Performance indicators to quantify this resiliency must also be introduced.

### 6.1.2 Objectives

This work firstly aims to augment the existing mathematical formulations to optimise investments and operations in steam networks to include and quantify load shedding formulations. In this way, optimal operations of steam networks with low operating reserves can also be established.

Using this formulation, investments may avoid investing in new equipments and opt for load shedding instead.

By carrying out a multi-period study, this work also aims to use steam network optimisation tools to demonstrate the feasibility of TSA solutions, to better estimate their costs and operability.

The state-of-the-art has revealed that notions of reliability and resilience have been explored in electric networks though little has been done in steam networks. To take into consideration the boiler failures, a new method is needed, as are metrics to judge the performance of the network.

A simulation method is therefore proposed to establish steam network resilience. Steam network operations are optimised while undergoing simulated boiler failures. Through the introduction of a mathematical formulation for load shedding into the traditional steam network investment and operations optimisation, it is possible to observe the steam network's ability to overcome stress events. A number of metrics are introduced to quantify the key properties of resilience in steam networks.

The resilience of steam networks are not addressed globally in this work as parametrisation of all possible perturbatory events would not be possible. The resilience of the networks is tested with regard to boiler failures, a common enough occurence in steam networks to figure in operational and investment planning.

This methodology is applied to the Typical Industrial Cluster case study in Section 6.3. Several different investment scenarios are generated and tested to gage their resilience and costs. The results of the TSA in Chapter 5 are included in these scenarios to demonstrate their feasibility.

## 6.2 Methodology

As a first step towards establishing the resilience of steam networks, the mathematical formulation for steam network operations optimisation is described in Section 6.2.1. A mathematical formulation for load shedding when facing undercapacity is then proposed in Section 6.2.2. Optimal investment formulations are established in Section 6.2.3.

The methodology for simulating boiler failures in steam networks is proposed in Section 6.2.4 with the Key Performance Indicators (KPI) to measure resilience in Section 6.2.5.

The proposed method uses MILP to reduce the computational complexity and solving time compared to MINLP methods. As a result, accuracies of operational costs, electricity generation and investments cost results are reduced compared to those of MINLP formulations, though the end consequence is questioned given the difficult task of accurate investment costing.

### 6.2.1 Optimal operations

Operations of a steam network can be optimised using a MILP formulation to define flows of steam from generating equipments, through headers, turbines and equipments in order to meet the demand.

Steam networks are modelled by sets of variables, parameters and constraints. Overall costs are minimised as the optimisation objective.

Each unit of the steam network can be defined according to its steam generation and consumption by pressure level. Units include boilers, cogeneration devices, PUs, turbines and letdowns. Equation 6.1 is a constraint defining the flowrate of steam through each unit $n$ for each time step $t$, $F_{n,t}$. It is bounded by its minimum possible flowrate $F_{min,n,t}$ and maximum $F_{max,n,t}$. The binary variable $y_{n,t}$ defines if unit $n$ is activated at time $t$.

$$F_{min,n,t} \cdot \mathbf{y_{n,t}} \leq \mathbf{F_{n,t}} \leq F_{max,n,t} \cdot \mathbf{y_{n,t}} \quad \forall n, t \tag{6.1}$$

For each of the $q$ PUs, flowrates are fixed for each time step. Equation 6.2 therefore removes all degrees of freedom from PUs, effectively fixing their flowrates and activation statuses, transforming them into parameters of the problem.

$$F_{\mathbf{min,q,t}} = F_{max,q,t} \quad \mathbf{y_{q,t}} = 1 \quad \forall q, t \tag{6.2}$$

Equation 6.3 is the most important constraint of the problem, defining the mass balance of each header $h$. Each unit of the model is associated to a header $h$, and can either belong to the set of units whose flowrates enter it ($I_h$) or exit it ($O_h$). This implies that mass balances must be closed for each header at all times. PU data must therefore be reconciled, as seen in Chapter 3.

$$\sum_{n \in O_h} \mathbf{F_{n,t}} - \sum_{n \in I_h} \mathbf{F_{n,t}} = 0 \quad \forall n, t, h \tag{6.3}$$

As PUs can simultaneously consume and produce steam at different pressure levels, a unit is defined for each pressure level it contributes to. An additional constraint is added to force the binary variables $y_{n,t}$ of such units to have the same value.

Letdowns are handled like a steam header with only one input and output. For each letdown $l$, a flow is defined entering it using the set $I_l$, and another exiting it, using set $O_l$. The outlet can be increased by desuperheating as seen in Equation 6.4. A factor $\alpha$ is therefore defined for each letdown, corresponding to the fraction of additional steam created through desuperheating. These factors depend on the temperature and pressure levels of the upstream and downstream flows. In this formulation, the desuperheating factor $\alpha$ is set as a parameter for the letdowns rather than a variable to avoid making the problem non-linear.

$$\sum_{n \in O_l} \mathbf{F_{n,t}} - \sum_{n \in I_l} \mathbf{F_{n,t}}(1 + \alpha_l) = 0 \quad \forall n, t, l \tag{6.4}$$

Turbines are defined using a mass balance at their inlets and outlets and a production of electricity. As the model is not thermodynamic the specific electricity $w_{n,t}$ generated by a turbine should be calculated beforehand based on its isentropic efficiency, its upstream temperature and pressure as well as the downstream pressure. The units can for example be in $[kWh/t]$. Part load accuracies would produce more accurate results, though these are not implemented in this work to reduce complexity.

Operational costs $c_{Op,n,t}$ of each of the $n$ units are calculated for each time step $t$ as seen in Equation 6.5. The flowrate of each unit is multiplied by its specific fuel cost $c_{n,t}$ (or other operational cost), from which its generated electricity earnings can be subtracted, based on the price of electricity at time $t$, $e_t$. Electricity generation equates to avoided electricity import from the national grid and therefore has negative costs.

Unit shutdowns and startups are considered to be instantaneous for all time steps, as no ramp-up and ramp-down times are considered. This implies that a sufficiently large time step should be chosen for the optimisation.

$$\mathbf{c_{Op,n,t}} = (c_{n,t} - e_t \cdot w_{n,t}) \cdot \mathbf{F_{n,t}} \quad \forall n, t \tag{6.5}$$

Cogeneration units are defined as boilers with an electricity production. Using these formulations, the costs of all units can be considered using their specific costs and electricity generation. Needless to say, different values must be chosen for different types of studies. Condensate returns are not taken into consideration in this model.

Through the use of sets, it is possible to elegantly define large steam network problems, within multiple sites. The level of detail can vary between applications. For example it is possible to study a steam network considering PU boundaries or individual sub units of the PUs.

### 6.2.2 Optimal operations with undercapacity

Undercapacity events take place when steam demand surpasses the steam generating capacity. If the activation of the letdowns rather than the turbines is not sufficient to remediate such a situation, load shedding must follow. In load shedding, PUs are systematically shut down until operating reserves become positive again.

The order of PU shutdown should be defined by operators based on their shedding priorities. These are based on technical and economic criteria and define the order in which to shutdown PUs when dealing with undercapacity. Technical criteria can include the ability for a PU to restart after a total shutdown, the amount of time required to shutdown and the dependence of other PUs on it. Economic criteria should relate to lost profits as a result of PU shutdown.

Calculating lost profits resulting from PU shutdown can be very complicated for a large industrial site, especially when PUs depend on one another as is often the case in the refining and petrochemical industries. The shedding priority is usually established for the steam network as well as the electricity network based on site knowledge. Several PUs can have the same shedding priority, meaning that its shutdown will be based on the appreciation of operators or an economic optimisation.

To permit PUs to be shed, Equation 6.2 is maintained, though the binary variables $y_{q,t}$ of shedable PUs must be set free. Equation 6.6 is added as a constraint of the model. The Equation forces PUs in group $p$ of Site $s$, $G_{p,s}$ to shutdown only once all units belonging to group $G_{p-1,s}$ have been shutdown.

$$\mathbf{y_{n,t}} \mid n \in G_{p,s} \geq \mathbf{y_{n,t}} \mid n \in G_{p-1,s} \geq ... \geq \mathbf{y_{n,t}} \mid n \in G_{1,s} \quad \forall n, t, s, p \tag{6.6}$$

When multiple process units belong to a same Group $p$, The optimiser chooses which PU to shutdown based on the penalty cost of unit $n$ at time $t$, $\mathbf{c_{Pen,n,t}}$ described in Equation 6.7 and economic criteria as a whole. For example, if a PU produces high pressure steam, the optimiser may keep it online as long as possible as it helps reduce the undercapacity.

$$\mathbf{c_{Pen,n,t}} = (1 - \mathbf{y_{n,t}})P_n \quad \forall n, t \tag{6.7}$$

From a theoretical point of view, Equation 6.7 should be sufficient to optimally decide the order in which to shutdown PUs. However, given the complexity of calculating penalty costs $P_n$ holistically, it is easier to guide the optimisation towards realistic operational modes using established industrial practices by using Equation 6.6. This optimisation can of course be used to challenge such practices if accurate values are made available for $P_n$.

### 6.2.3 Optimal investments

With the following formulation it is possible to identify optimally sized steam generating equipment investments to supply the steam network demand.

Investments in a new unit $n$ can be defined by its fixed $I_{fix,n}$ and variable investment costs $I_{var,n}$. They should also be defined according to minimum and maximum flowrates ( $F_{min,n}$ and $F_{max,n}$) and binary variables $y_{n,t}$ to determine if they are activated or not in the optimisation.

Binary variables $y_n$ are defined for each investment to determine whether or not it is activated in any of the time steps. The maximum installed capacity can also be established as seen in Equation 6.8.

$$\begin{aligned} \mathbf{y_n} &\geq \mathbf{y_{n,t}} \quad \forall n \\ \mathbf{F_n} &\geq \mathbf{F_{n,t}} \quad \forall n \end{aligned} \tag{6.8}$$

Costs should be based on the pricing philosophy of each industrial site, though it is recommended to us annualised costs to prevent investments from dominating overall costs of the system. The investment costs $\mathbf{c_{Inv,n}}$ of each proposed equipment are defined by Equation 6.9. If the equipment has not been selected by the optimisation, its investment costs will be zero.

$$\mathbf{c_{Inv,n}} = I_{fix,n} \cdot \mathbf{y_n} + I_{var,n} \cdot \mathbf{F_n} \quad \forall n \tag{6.9}$$

As investment costs are non-linear, using a linear formulation has the limitation of not taking into consideration economies of scale [93]. It is therefore recommended to define multiple investments for each technology, based on their capacity ranges. Piece wise linearisation techniques can be used to estimate their costs within certain ranges, which can be set using the minimum and maximum allowed flowrates $F_{min,n,t}$ and $F_{max,n,t}$ [102], though they are not used in this work.

The objective function of the steam network is shown in Equation 6.10. This objective calculates operational costs, penalty costs, electricity production and investment costs of all units. Results from each time step are multiplied by the duration of the time step $d_t$ to calculate overall costs. Using the formulation, load hsedding may be an economically optimal alternative to investments.

$$Obj = \min \sum_n (\mathbf{c_{Inv_n}} + \sum_t d_t \cdot (\mathbf{c_{Op,n,t}} + \mathbf{c_{Pen,n,t}})) \tag{6.10}$$

The identified investment solutions of this algorithm correspond to the minimum sizes that can meet the demand, without considering maintenance operations or redundancy. Sensitivity analyses may be performed to establish minimal investments when considering maintenance of certain equipments, or a traditional manual approach.

### 6.2.4 Simulation of boiler failures

Though occasional, boiler failures are inevitable in steam networks, with potentially high impacts and costs. As boilers age, the likelihood of failures increases. While simultaneous boiler failures are very unlikely, as they can last several days, the probability of two failures overlapping becomes more significant.

Combinatorial mathematics can be used to calculate such a probability [103]. Consider the 7 boilers of the Typical Industrial Cluster with constant failure rates of $\lambda = 1/365$, the probability of one of them failing on a given day is 0.3%. If a failure takes place, the probability of having a second failure within 4 days is 41.8% [1]. Figure 6.1 illustrates such an example where overlapping boiler failures significantly reduce the available steam generation capacity of a cluster.

A risk analysis could be carried out to calculate the probability of simultaneous boiler failures occurring at time $t$, however the combinatorial problem combined to varying steam demand means that a purely statistical analysis is not sufficient to quantify the risks of steam network operations being disturbed by boiler failures. The ability of desuperheaters to boost steam output when facing undercapacity further complicates the question.

For each combination of boiler failures, the network must then be optimised to establish what combination of load shedding and equipment operation takes place (letdown desuperheaters can perhaps remove the need for load shedding). A simulation (space exploration method) is therefore proposed to calculate the operability properties of the steam network when facing boiler failures, thus avoiding complex mathematical calculations.

The algorithm is, illustrated in Figure 6.2. Different combinations of available equipments and investment proposals can be compared to establish which is most resilient. Investments can be selected manually or using the formulation in Section 6.2.3.

1. The steam networks' architecture (flows) are defined, as well as the multi-period data and investment proposals. Identical time steps are required for each period.
2. Optimisation of operations for proposed investments: Design costs for investment propositions are calculated. No boiler failures are simulated in this step.
3. Simulation of operations: $m$ individual optimisations of the steam network are performed.
    (a) Monte-Carlo sampling is used to randomly shutoff boilers based on their mean failure rates $\lambda_b$ and maximum failure duration $\delta_b$, as described in Equations 6.11 and 6.12.
    (b) The steam network optimisation is run for each of the $m$ iterations of the simulation.
    (c) The objective function as defined in Equation 6.10 is recorded for each iteration. A record is also kept of all load shedding events to determine the resilience of the system (see KPIs in Section 6.2.5).
    (d) The simulation is considered to have converged once both conditions defined in Equation 6.14 have been met.
    (e) The investment, operational and penalty costs ($Obj$) as defined in equation 6.10 can be recorded for each iteration as well as the investment configurations obtained and performance indicators.

1. The probability $P$ of boiler failures following each other $k$ days apart can be calculated using the formula developed in [103], where $n$ is the number of boilers, $\lambda = 1/365$ the constant failure rates and $k$ the number of days separating two boiler failures: $P = 1 - \frac{(364-nk)!}{365^{n-1} \cdot (365-n(k+1))!}$.

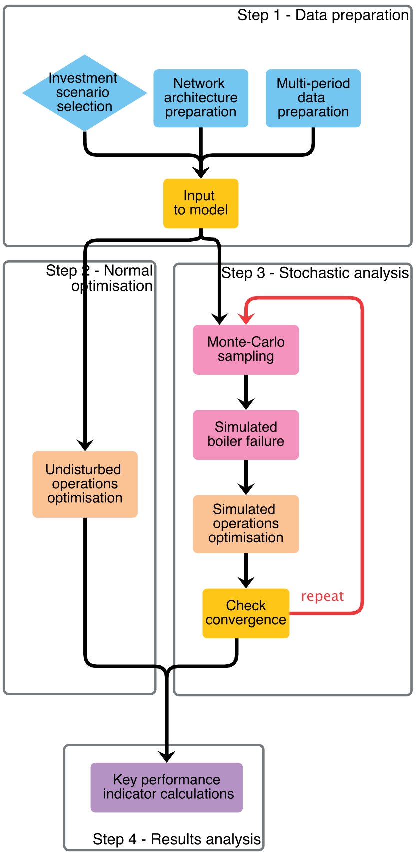



Figure 6.2 – Algorithm for simulating boiler failures.

4. The economic and operability results of the different investment scenarios can be compared.

The example given in Figure 6.1 was created using the formulations in Equations 6.11 and 6.12 to randomly shutoff boilers based on their failure properties. A value $x_{b,t}$ is randomly generated between 0 and 1 for each boiler and each time.

$$\begin{aligned} \mathrm{x_{b,t}} &= U(0,1) \quad \forall b,t \\ \delta_{\mathrm{b,t}} &= U(0,\delta_b) \quad \forall b,t \end{aligned} \tag{6.11}$$

If $x_{b,t}$ is smaller than $\lambda_b$, its minimum and maximum flowrate are set to zero for a duration of time $\delta_{b,t}$ randomly chosen between 0 and $\delta_b$ (Equation 6.12). This prevents boiler $b$ from being able to produce steam for duration of time $\delta_{b,t}$.

$$\text{If} \quad x_{b,t} < \lambda_b \quad \begin{cases} \mathbf{F_{max,b,t}}, \ldots, \mathbf{F_{max,b,t+\delta_{b,t}}} = 0 & \forall b, t \\ \mathbf{F_{min,b,t}}, \ldots, \mathbf{F_{min,b,t+\delta_{b,t}}} = 0 & \forall b, t \end{cases} \tag{6.12}$$

Failures of each boiler $b$ are defined by their constant failure rates $\lambda_b$ and maximum failure durations $\delta_b$. $\lambda_b$ calculated using equation 6.13 with the $MBTF_b$ (Mean Time Between Failure of boiler $b$), using observed industrial data.

$$\lambda_b = 1/MBTF_b \tag{6.13}$$

In reality failure rates are not constant but rather a function of time since last failure and age of the equipment [104]. The frequency of failures will in reality observe the shape of an inverted bell, with the highest frequency of failures in its early and end of life. The constant failure rate approach is used to simplify the problem and reduce its overall number of variables. Variable failure rates would require much higher equipment knowledge. Similarly, using maximum failure durations $\delta_b$ is not entirely realistic as depending on the severity of the failure, the durations can become very long. For example a fire could lead to boiler permanent decommission.

This algorithm is a space exploration simulation to identify possible boiler failure and operations combinations. At each iteration, the steam network optimisation identifies the best compromise between load shedding, investment and costs. Its convergence criteria are met when $\sigma_{Obj}$ the normalised standard deviation of $Obj_m$ [36] is smaller than a threshold value $\epsilon$ and $m_0$ iterations have been completed.

$$\text{Convergence when} \quad \begin{cases} m > m_0 \\ \frac{\sigma_{Obj}}{\sqrt{m}} < \epsilon \end{cases} \tag{6.14}$$

### 6.2.5 Key performance indicators

No scientific definition exists for the term resilience. In electricity networks, it is often mentioned in parallel to other quantifiable terms such as operability. A similar approach is taken here, in which the operability of a steam network is defined as its ability to supply its steam demand. Two operability KPIs are introduced ($\bar{N}$ and $X_N$). Cost related KPIs are also used to quantify the operations and setbacks related to load shedding, namely the penalty.

**Operability** The notion of operability is introduced as a measure of the expected frequency of shedding.

- Expected operability $\bar{N}$: The total number of recorded shedding events within a given optimisation $N_s$ is divided by the total number of binary decisions $N_y$ made about shedable units and subtracted from one, Equation 6.15. The expected operability $\bar{N}$ defined as the mean operability of each run.

- The operability interval $X_N$: $X_N$ the fraction of runs $X$ which have an operability higher than $N$. For example if 95% of runs have an operability higher than 99.9 we have $X_{99.9} = 95\%$.

$$\bar{N} = 100 \times (1 - \frac{N_s}{N_y}) \quad [-] \tag{6.15}$$

The case study is made up of 17 shedable units and utilities defined by 36 steam consumptions or productions (various pressure levels considered), with 365 time steps. The total number of binary decisions for shedable units is therefore $N_y = 35 * 365 = 13140$. If 100 shedding events took place in a run, the operability would be 99.2%. An operability of 99.9% implies less than 20 shedding events in the entire cluster over a year.

**Expected costs** Operational and penalty costs may be significantly influenced by undercapacity. Turbines may be deactivated in favour of letdowns, meaning that less electricity is generated. Penalty costs can be very significant as well.

A statistical analysis of the total costs of each iteration of the simulation reveals how much variation can be expected from a given configuration. Box plots offer a convenient way to visualise the data, showing mean, median, standard deviation and outlier values.

## 6.3 Application to Typical Industrial Cluster

Chapter 2 described the configuration of the Typical Industrial Cluster (TIC) in detail. It stated that due to new regulations, the two Central Boilerhouse (CB) boilers would have to go offline. Consequently, investments in new steam generating equipments must be made to ensure the operability of the TIC. Using the above defined algorithm, resilient investment solutions are identified to replace the current CB boilers.

To identify resilient investments, the following steps are carried out:

1. Optimisation of TIC steam network under actual conditions (Section 6.3.1).
2. Evaluation of optimal conditions in the case of CB boiler decommissions (Section 6.3.2).
3. Evaluation of Hot Water Network feasibility (Section 6.3.3).
4. Discussion on investment options to replace CB boilers (Section 6.4).
   - Generation of investment scenarios (Section 6.4.1).
   - Simulation of investment scenarios (Section 6.4.2).

The MILP formulation defined above was applied to the TIC using the reconciled data from Chapter 3. The 365 time steps of the model were used. The graphical representations display 8760 hours as the 365 days are multiplied by their number of hours. To limit the problem size, the PUs were defined by their consumption and production of steam, the sub units were not included in the data.

The steam price properties described in Table 2.3 were used, namely a steam price of 18 $/t for the Site R and P boilers and 25 $/t for steam produced by the CB boilers. The demineralised water price was set at 5 $/t and the sale price of generated electricity at 112 $/MWh.

The mathematical formulation was input into the AMPL [106] software and optimised by the Gurobi optimiser [107].

Using the set definitions used in the mathematical formulation, it was possible to define Site R, Site P and the CB as separate networks, though the optimisation aims to minimise overall costs for all three of them. As the CB boilers belong to a third party, rather than financially account for the steam produced, the steam transferred to the Sites R and P is billed.

The flowrates of steam through turbines was left as a variable of the problem, though a brief comparison of results with those generated from the recorded historical data is made in Section 6.3.1 to show the advantages of optimisation tools.

### 6.3.1 Current operations

Figure 6.3 shows the optimised pathways of steam resulting from the optimisation of the network. As no investments were defined for this run, only the operational costs are optimised.

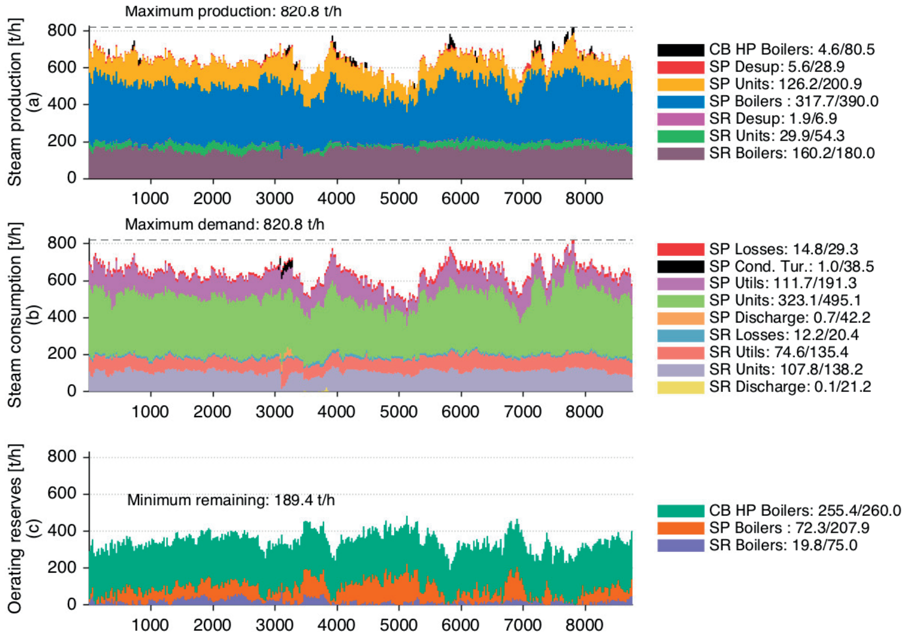



Figure 6.3 – Steam production (a), consumption (b) and operating reserves (c) of Typical Industrial Cluster in current configurations.

Graph (a) of Figure 6.3 details the steam production by boilers, process units and the desuperheaters. The legend indicates mean and maximal values. Close inspection of Graph (a) reveals that the desuperheaters of Site P activate only when demand is high. In such situations, either the turbines have been bypassed in favour of the letdows, or more likely, the turbines are in operation, though at their maximum capacity meaning that steam is passed through letdowns to meet the down stream demand.

Boilers supply 482.5 t/h for the cluster on average with a peak load of 640.6 t/h. When combined to the load of the desuperheaters (mean 7.5 t/h and maximum 30.6 t/h), the average supply of steam becomes 489.9 t/h with a peak value of 662.4 t/h.

Graph (b) of Figure 6.3 shows the consumption of steam by the site PUs and Utility requirements. The label SP Cond. Tur. corresponds to condensation turbine PT3 of Site P. SR Discharge and SP Discharge respectively correspond to atmospheric letdowns RL3 and PL3, which vent steam to the atmosphere as a result of excess 5 barg steam.

Graph (c) of Figure 6.3 shows the operating reserves of the TIC, which are always above 189.4 t/h. The CB boilers are the least used, a logical result given their more expensive steam price, they are however necessary to supply required steam.


Figure 6.4 – Operational costs of steam network in current conditions for Site R (a), Site P (b), CB (c) and the overall cluster (d).

Figure 6.4 shows the operational costs of Site R in (a), Site P in (b), The CB in (c) and the combined costs of the cluster in (d). No penalty costs are present at any point as no load shedding takes place in this optimisation. Import costs in dark blue correspond to the price paid for steam bought from the CB boilers. Its equivalent is shown in red in graph (c). These are not present in graph (d) though its overall costs are correct.

The green areas of the graphs of Figure 6.4 show the costs of steam generation. As Site P has a higher steam demand than Site R, these costs are significantly higher for it. The salmon areas show the gains from electricity generation. These correspond to avoided electricity import from the national grid.

The steam generation costs of the TIC are $76.5 \times 10^6$ \$/yr, with $-26.1 \times 10^6$ \$/yr in electricity generation, making a total of $50.7 \times 10^6$ \$/yr.

For comparison, the same optimisation was run using the recorded flowrates of the turbines of the TIC. These were therefore set as parameters of the problem. The key results are presented in Table 6.1.

Table 6.1 – Comparison of key results of optimal operations compared with actual operations.

| | Costs [$\times 10^6$ \$/yr] | | | Boiler [t/h] | | Desup. [t/h] | | Steam supply [t/h] | |
|---|---|---|---|---|---|---|---|---|---|
| | Total | Penalty | Elec. | Mean | Max | Mean | Max | Mean | Max |
| Actual | 54.5 | 0.0 | -21.5 | 475.0 | 635.3 | 15.0 | 45.3 | 490.0 | 662.4 |
| Optimised | 50.7 | 0.0 | -26.1 | 482.5 | 640.6 | 7.5 | 30.6 | 489.9 | 662.4 |

Reduced electricity generation is the principle reason behind the differences in costs. The optimised network produces the same amount of steam, though more of it is sent into the turbines leading to reduced letdown use. Using the mathematical optimisation tools it is therefore possible to improve the cogeneration potential of the steam network compared to recorded data and therefore reduce costs by 6.9% ($3.8 \times 10^6$ \$/yr).

As the steam consumption stays the same, optimised operations translate to reduced import of electricity from the national grid rather than direct fuel economies.

### 6.3.2 Load shedding due to CB boiler decommission

In this application of the methodology, the CB Boilers are taken offline. The operations of the steam network are evaluated in their absence to demonstrate the use of the load shedding formulations defined in Section 6.2.2. Given the parameters of the problem and the shedding properties defined in Table 2.11, load shedding occurs in both Sites R and P.

Figure 6.5 shows the key results of the optimisation. In graph (a) we can see the steam consumption of the units and utilities. Graph (b) shows a zoom of the same data, where we can see that the demand for steam (in red) cannot always be met by the boilers. Graph (c) shows an overview of the shedding events. Site R sheds on three occasions, while Site P sheds several times after hour 6000.

Graph (d) of Figure 6.5 shows the economic results of the optimisation. The penalty costs are shown in blue, significantly higher than normal operating costs. When load shedding takes place, the electricity production also collapses, further impacting the costs of the system. This is a logical result as the optimisation favours letdowns to turbines when operating reserves are low so as to boost steam production with the desuperheaters.

The penalty costs of Sites R and P are respectively $1.2 \times 10^6$ for 2.0 tons of steam not supplied and $1.3 \times 10^6$ \$/yr for 7.5 tons of steam not supplied. The peak load shedding occurs on day 312 (hours 7488-7512), in which Site P sheds the PT1 and PT2 turbines, the Utilties (U), Utilities (U1), Process Unit D and Process Unit C, respectively with shedding priorities 1 to 5 as defined in Table 2.11.

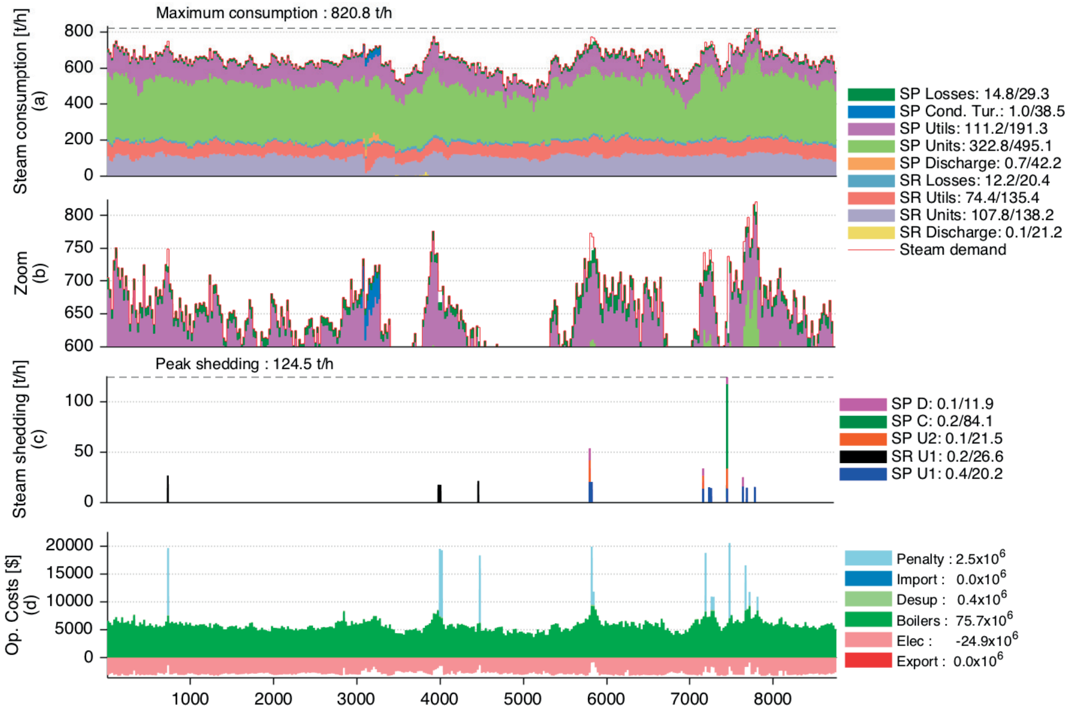



Figure 6.5 – Steam consumption (a), zoom on its high demand (b), load shedding occurrences (c) and overall costs of the Typical Industrial Cluster (d) when CBs offline.

Table 6.2 – Comparison of key results of optimal operations with and without the CB boilers.

| | Costs [$\times 10^6$ \$/yr] | | | Boiler [t/h] | | Desup. [t/h] | | Steam supply [t/h] | |
|---|---|---|---|---|---|---|---|---|---|
| | Total | Penalty | Elec. | Mean | Max | Mean | Max | Mean | Max |
| With CB | 50.7 | 0.0 | -26.1 | 482.5 | 640.6 | 7.5 | 30.6 | 489.9 | 662.4 |
| Without CB | 53.7 | 2.5 | -24.9 | 479.7 | 570.0 | 9.2 | 47.3 | 488.8 | 608.8 |

Table 6.2 describes some complimentary results. As mentioned above, electricity production is reduced as a result of load shedding and reduced high pressure steam availability. The mean steam supply is only slightly diminished as a result of the CBs going offline, which indicates the steam networks can operate at normal steam loads. However, high demand is difficult to reach for both sites leading to load shedding.

The combined installed steam generation capacities of Site R and P are equal to 570 t/h. The desuperheaters are able to provide a peak 25.9 t/h of additional steam in Site R and 33.5 t/h in Site P. In this way, the peak steam supply of the TIC can reach 608.8 t/h despite the absence of the CBs, though it is not enought to meet the steam demand.

### 6.3.3 Feasibility of Hot Water Network

The TSA retrofit solutions of Chapter 5 promised 45.0 MW (74.3 t/h) of avoided steam consumption through the installation of the Hot Water Network (HWN). These findings can be tested and verified using the above defined methods. The HWN is therefore included in the steam network optimisation by adapting the steam demand of the Site P units and including a Kettle. The Kettle consumes 5 barg steam in Site P to prepare hot water when additional supply is necessary.

Figure 6.6 shows the consumption of steam before (a) and after (b) addition of the HWN network. Table 6.3 compares the other key properties of the system. The CB boilers are considered to be online for both systems.

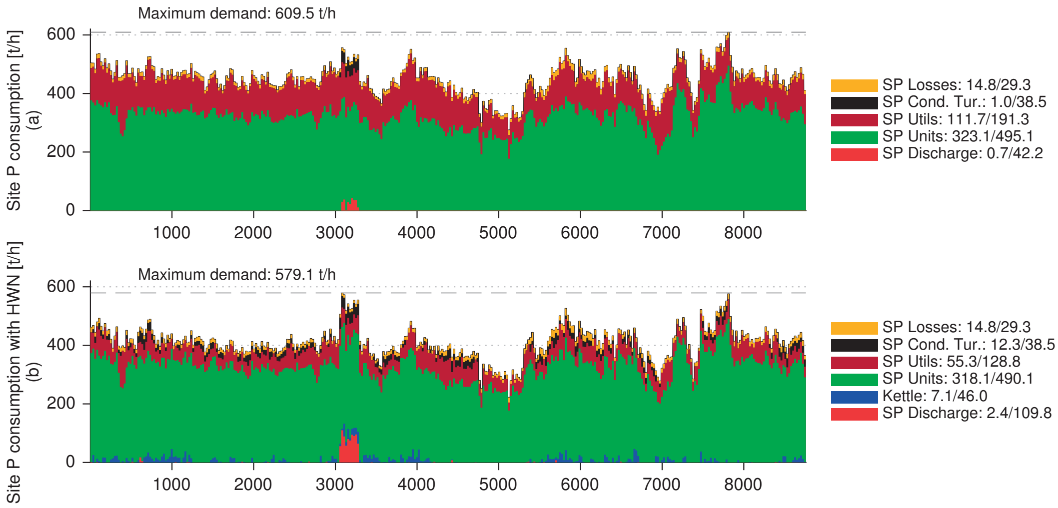



Figure 6.6 – Steam consumption of Site P without HWN (a) and with HWN (b)

Table 6.3 – Comparison of key results of optimal operations for the Cluster with and without the Hot Water Network.

| | Costs [$\times 10^6$ \$/yr] | | | Boiler [t/h] | | Desup. [t/h] | | Steam supply [t/h] | |
|---|---|---|---|---|---|---|---|---|---|
| | Total | Penalty | Elec. | Mean | Max | Mean | Max | Mean | Max |
| Without HWN | 50.7 | 0.0 | -26.1 | 482.5 | 640.6 | 7.5 | 30.6 | 489.9 | 662.4 |
| With HWN | 46.8 | 0.0 | -21.7 | 430.8 | 579.9 | 5.1 | 16.6 | 435.8 | 595.8 |

Visually it is evident that steam consumption of the PUs and utilities is reduced as a result of the introduction of the HWN. The PU and utility consumption demand decreases from 308.6 t/h to 234.3 t/h, the difference being equal to 74.3 t/h [2]. This indicates that all avoided steam is properly taken into consideration.

2. The steam demand is calculated as the difference steam consumption and PU production which is not shown in Figure 6.6.

The graphs show atmospheric discharge around hour 3000 in red. As a result of using the HWN, steam consumption is reduced, therefore steam exported by Units A and E of Site P are no longer able to find consumers which explains why the atmospheric discharge increases.

It can also be seen that the condensation turbine PT3 (SP Cond. Tur.) is much more frequently used by Site P, with an average 12.3 t/h compared to 1.0 t/h in the absence of the HWN. It can be assumed that excess steam is in cause as well though it may also be related to the thermoeconomic optimisation favouring the use of turbines. Further analysis would be necessary to clarify this question.

The Kettle requires a mean 7.1 t/h of steam to supply hot water to the HWN with a peak consumption of 46.0 t/h as a result of unbalanced hot water generation and consumption.

The overall steam consumption reduction of Site P as a result of the HWN is equal to 52.4 t/h rather than the expected 74.3 t/h. This is due to the Kettle requirements and an increased use of the condensation turbine and atmospheric discharge.

These results highlight that the TSA method is not sufficient to evaluate the thermoeconomic performance of an investment solution and that additional utility network analysis is required.

## 6.4 Investment options

Several investment options are discussed below, as well as their pricing strategies.

As mentioned in Section 6.2.3, investments are defined by their fixed costs $I_{Fix}$ and variable costs $I_{Var}$. Equation 6.16 is used to calculate the annuity $a_{r,n}$ of the investments [105] for an expected lifetime of $n = 20$ years and an interest rate $r = 5\%$. The annualised investment cost $i$ is obtained by multiplying the annuity by the total investment costs $I$ as in Equation 6.17

$$a_{r,n} = \frac{r \cdot (1+r)^n}{(1+r)^n - 1} \quad [yr^{-1}] \tag{6.16}$$

$$i = I \cdot a_{r,n} \quad [\$/yr] \tag{6.17}$$

### Hot Water Network

The Hot Water Network (HWN) identified thanks to the Total Site Analysis in Chapter 5 and discussed above is included in the investment options to replace the CB boilers.

The required equipments for such a HWN are detailed in Section 5.4. Their overall investment cost for works, installation and related disturbances are estimated to be around $I_{Fix,HWN} = 20 \times 10^6$ $, without any variable costs. As the site HWN network benefits Site P, its investment costs are the responsibility Site P.

### High pressure 90 barg boilers

Boilers identical to the original CB boilers are proposed, producing steam at 90 barg and 450°C. Their investment costs are $I_{Fix,HP} = 25 \times 10^6$ $ and their variable costs are $I_{Var,HP} = 33 \times 10^4$ $/t of installed capacity. These costs include the pipes required to connect them to Sites R and P. The boilers can be placed in the same area as the existing CB boilers and generate steam at 18 $/t as no third party is involved.

### Medium pressure 30 barg boilers

The results of the TSA and PU analysis showed that the process demand for 90 barg steam in Sites R and P is limited to turbines to power compressors. For this reason medium pressure (30 barg) boilers are proposed to replace the existing CB boilers. These are cheaper to install and operate since the materials and design are different given the lower pressures.

Their investment costs are $I_{Fix,MP} = 15 \times 10^6$ $ and their variable costs are $I_{Var,MP} = 22 \times 10^4$ $/t of installed capacity. These costs include the pipes required to connect them to Sites R and P. The boilers can be placed in the same area as the existing CB boilers and should generate steam at 15 $/t.

As Site R consumes 20 barg steam, the 30 barg steam is letdown to 20 barg and coupled to a desuperheater to boost its production by 3.1%.

### Cluster symbiosis pipes

The TSA considered the entire cluster to be one thermodynamic system. To replicate this approach in the steam networks, two pipes are linked between Site R and P. These pipes offer the possibility for the sites to make use of each others steam when operating reserves are low. As peak demand does not occur simultaneously at both sites, these are an interesting option to avoid investment in boilerhouses.

- Symbiosis $R \rightarrow P$: 90 barg steam is sent from Site R to Site P's 30 barg header, coupled to a desuperheater (7.3% boost).

  No fixed investment costs are present. The variable costs are $I_{Var,SRP} = 20 \times 10^3$ $/t of installed capacity. The line is closed when operating reserves at Site R are equal to zero.

- Symbiosis $P \rightarrow R$: 30 barg steam is sent from Site P to Site R's 20 barg header, coupled to a desuperheater (3.1% boost).

  No fixed investment costs are present. The variable costs are $I_{Var,SPR} = 10 \times 10^3$ \$/t of installed capacity. The line is closed when operating reserves at Site P are equal to zero.

One could consider creating a two way flow pipe between both Sites to share 5 barg steam, though this would not be advised as pressure losses and variations in pressures between sites would make it untenable.

As the site symbiosis projects are considered to belong to a site unification project, no costs are associated to their operations.

#### Overview

Table 6.4 shows a resume of the proposed annualised investments in the steam network, as well as their operating costs.

Table 6.4 – Investment properties.

| | Max. [t/h] | Price [\$/t] | $i_{Fix}$ [ $\times 10^3$ \$/yr] | $i_{Var}$ [ $\times 10^3$ $\$/t \cdot yr$] |
|---|---|---|---|---|
| HWN | | | 1600 | |
| HP gas boiler | 130 | 18 | 200 | 26.4 |
| MP gas boiler | 80 | 15 | 120 | 17.6 |
| $Symbiosis R,P$ | 120 | | | 1.6 |
| $Symbiosis P,R$ | 120 | | | 0.8 |

### 6.4.1 Scenario generation

Four investment strategies are defined to identify investment options for the TIC. The aim of these scenarios are to identify investment configurations that can be simulated in Section 6.4.2.

The CB boilers are taken offline for each scenario. Scenario 1 is a replication of the existing configuration. The optimal investment formulations defined in Section 6.2.3 are used for scenarios 2 to 4. The investments are defined in Table 6.4.

1. Scenario 1 - *As is*: Two 130 t/h 90 barg boilers are fixed as investments.
2. Scenario 2 - *Bare minimum investments*: Investments are optimally identified to meet current demand without any oversizing.
3. Scenario 3 - *Single boiler maintenance*:
   (a) Scenario 3 R: Boiler 2 of Site R is taken offline. Investments are optimally identified to meet demand.

   (b) Scenario 3 P: Boiler 3 of Site P is taken offline. Investments are optimally identified to meet demand.
   (c) Scenario 3: The investments identified in Scenarios 3R and 3P are combined. The biggest capacities are chosen.
4. Scenario 4 – *Simultaneous boiler maintenance*: A boiler is taken offline in both Sites and the optimal investments are identified.

Given the complexity of the HWN and the disturbances it could cause to the TIC during its installation, its feasibility may still be in question. Therefore, each scenario is run with and wihtout the HWN to better demonstrate its interest.

Both boilers are defined twice in the investments to permit the optimisation to choose several them if it so desires. The generated investment scenarios are detailed in Table 6.5. The results of Scenarios 3R and 3P are shown in grey as it is their combined investments that interest us. The total installed capacity corresponds to the new investments plus the existing capacity of Site R and P's boilers ($2 \times 90 + 3 \times 130$ t/h).

Without the HWN, Scenario 1 leads to the highest investment costs, with $7.6 \times 10^6$ \$/yr. Scenario 2 logically leads to the lowest overall costs, with a small investment in a MP boiler and the symbiosis pipes. Scenario 3 requires $4.8 \times 10^6 \$/yr$ to invest in three boilers and both symbiosis pipes. Scenario 4 invests in three boilers and only one symbiosis pipe.

It should be noted that Scenarios 3P and 4 include load shedding in the optimal operations to reduce required investments.

With the HWN, results follow similar trends. As previously demonstrated, operational costs are reduced though investment costs increase in Scenarios 2,3 and 4. No load shedding is required in any of the scenarios.

At no point do any of the optimised investments propose to purchase two HP boilers, though two MP boilers appear interesting when a boiler is offline at Site P.

Table 6.5 – Investment scenarios.

| | Costs [$\times 10^6$ \$/yr] | | | | | Installed capacity [t/h] | | | | | | | Load Shedding | | Steam Supply | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Total | Inv. | Op | Elec. | Penalty | Total | HP 1 | HP 2 | MB 1 | MB 2 | Sym. R-P | Sym. P-R | Mean [t/h] | Max [t/h] | Mean [t/h] | Max [t/h] |
| *No HWN* | | | | | | | | | | | | | | | | |
| Scenario 1 | 57.6 | 7.3 | 76.5 | -26.1 | 0.0 | 830 | 130 | 130 | | | | | 0.0 | | 489.9 | 662.4 |
| Scenario 2 | 50.8 | 0.8 | 76.0 | -26.0 | 0.0 | 605.4 | | | 35.4 | | 13.6 | | 0.0 | | 489.9 | 662.4 |
| Scenario 3R | 53.0 | 2.9 | 76.0 | -25.9 | 0.0 | | 83.5 | | 34.5 | | | 5.8 | 0.0 | | 489.9 | 662.4 |
| Scenario 3P | 53.2 | 3.2 | 75.5 | -25.5 | 0.1 | | 30.0 | | 80.0 | 38.6 | 28.3 | | 0.1 | 20.2 | 489.8 | 642.2 |
| Scenario 3 | | 4.8 | | | | 772.1 | 83.5 | | 80.0 | 38.6 | 28.3 | 5.8 | | | | |
| Scenario 4 | 55.4 | 5.4 | 75.4 | -25.5 | 0.1 | 809.4 | 105.2 | | 80.0 | 54.2 | | | 0.1 | 20.2 | 489.9 | 642.2 |
| *With HWN* | | | | | | | | | | | | | | | | |
| Scenario 1 | 55.4 | 8.9 | 68.3 | -21.8 | 0.0 | 830 | 130 | 130 | | | | | 0.0 | | 435.9 | 595.8 |
| Scenario 2 | 48.2 | 1.6 | 68.3 | -21.8 | 0.0 | 570 | | | | | | 31.3 | 0.0 | | 435.8 | 583.3 |
| Scenario 3R | 50.5 | 3.8 | 68.3 | -21.6 | 0.0 | | 81.8 | | | | | 39.3 | 0.0 | | 435.8 | 583.3 |
| Scenario 3P | 49.8 | 3.7 | 67.6 | -21.4 | 0.0 | | 24.1 | | 74.9 | | 21.8 | | 0.0 | | 435.7 | 583.3 |
| Scenario 3 | | 3.9 | | | | 726.7 | 81.8 | | 74.9 | | 21.8 | 39.3 | | | | |
| Scenario 4 | 52.1 | 6.0 | 67.5 | -21.3 | 0.0 | 761 | 89.4 | | 80.0 | 21.6 | | 4.5 | 0.0 | | 435.6 | 583.3 |

### 6.4.2 Simulation of scenarios

The investment scenarios identified in 6.4.1 were each simulated using the algorithm defined in Section 6.2.4. The current configuration was also simulated to provide a reference.

The failure properties of the existing boilers are defined using the properties in Table 2.3. New boilers were given a constant failure rate of $\lambda_b = 1/365$ and a maximum failure duration of $d_b = 8$ days. The HWN as a whole was considered to be impervious to failures.

In the previous sections, the maximum installed capacity of boilers was identified. No minimum flowrate was set for those investments. To increase the realism of the proposed scenarios, the minimum flowrate of the boilers were set at 25% of their installed capacity.

#### Simulation of current configuration

Figure 6.7 shows the operational costs of each iteration of the simulation of boiler failures in the TIC under its current configuration with the old CB boilers. The optimal operational costs without any boiler failures are 50.7 $\times 10^6$ \$/yr.

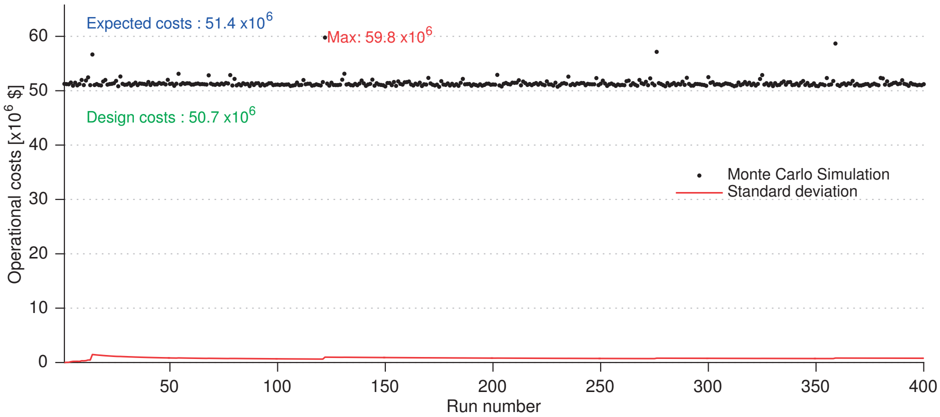



Figure 6.7 – Simulated costs of current steam network when facing boiler failures.

Simulated boiler failures lead to sub-optimal network operations, load shedding and therefore penalty costs, shown in black. The mean value of the simulation runs, shown in blue is $51.2 \times 10^6$ \$/yr. It corresponds to the expected costs of the system. The red line shows the standard deviation of the expected costs, and is equal to $0.8 \times 10^6$ \$/yr after 400 iterations.

Figure 6.8 shows the 100 most costly simulated runs for the current configuration. Graph (a) shows the sorted costs (descending) and graph (b) shows the equivalent peak load shedding for each of the runs. Logically, the highest load shedding events correspond to the highest costs. Level 5 load shedding is activated in Site P and level 7 in Site R in the worst cases. In practise this would correspond to a quasi total cluster shutdown and likely occurs as a result of combined boiler failures.

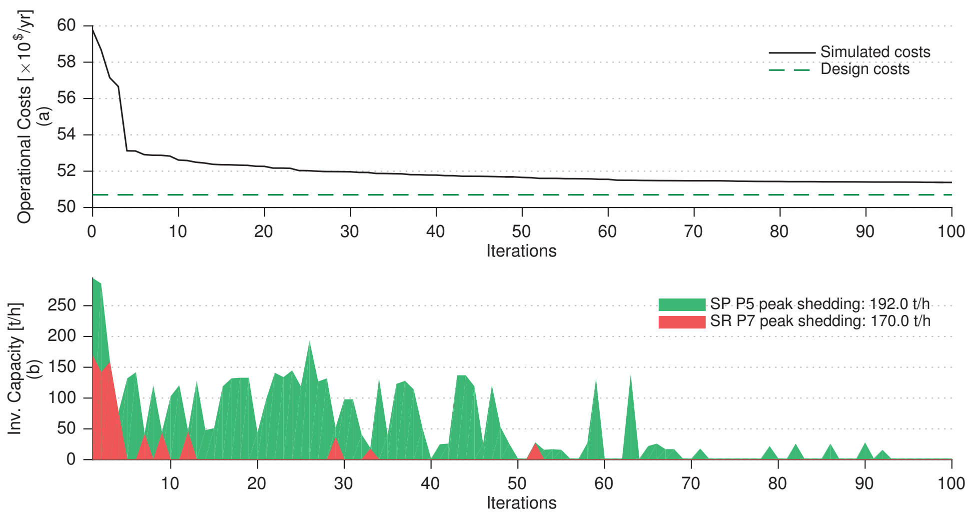



Figure 6.8 – Simulation results for 100 most costly runs of the current steam network, costs (a) and the required load shedding (b).

Figure 6.8 also shows that despite the absence of load shedding, costs can be significantly higher than the design costs. Iteration 40 shows almost 1.9 $\times 10^6$ \$ in additional costs without any load shedding. Limited boiler supply also translates to reduced turbine use and therefore avoided income.

The average operability of the network under its current configuration is $\bar{N} = 99.98\%$. This translates to less than 2.5 shedding events per iteration on average. The operability threshold is equal to $X_{99.9} = 97.25$, which means that 97.25% of runs had an operability higher than $\bar{N} = 99.9\%$.

### Simulation of investment scenarios

Table 6.6 shows the key results for each of the simulated scenarios. These can be compared to the current configuration for reference purposes. The total expected costs are shown in blue and analysed below. Results are also shown visually in Figure 6.9.

- Scenario 1: This scenario has the most expensive investment costs with or without the HWN due to the two oversized 90 barg boilers. The expected costs are quasi identical to the design costs, with very little shedding events. The average operability $\bar{N}$ is practically 100% in both cases, and the operability threshold $X_{99.9}$ is above 97% in both cases. The performance surpasses that of the current configuration (S0) as the new HP boilers fail less often than the existing boilers.

  Graph (b) of Figure 6.9 shows that the variation in operational costs is very small with or without the HWN, the same is true for the operability. Due to the expensive boilers, estimated costs are among the most expensive, as can be seen in graph (a).

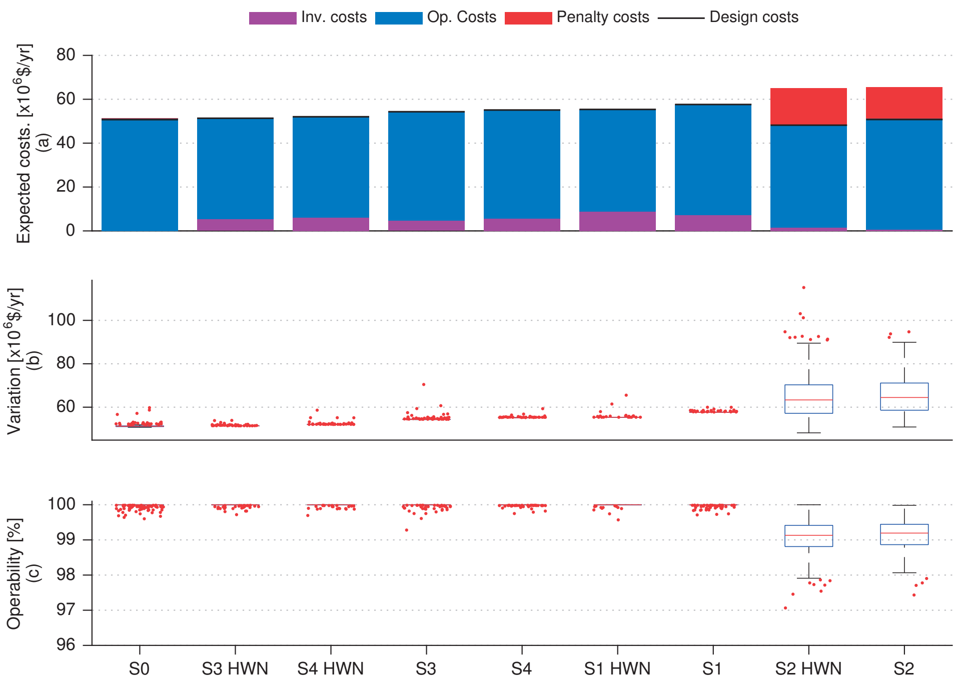



Figure 6.9 – Expected costs (a), variation in costs (b) and variations in operability (c) of investment scenarios.

Table 6.6 – Key results of boiler failure simulations on scenarios.

| | Costs [$\times 10^6$ \$/yr] | | | | | | | | Events [–] | | Load Shedding Peak level | | Operability [%] | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Design Costs | | | Expected Costs | | | | | | | | | | |
| | Total | Inv. | Op. | Total | Inv. | Op. | Penalty | Deviation | Mean | Max | Site R | Site P | $\bar{N}$ | $X_{99.9}$ |
| Scenario 0. | 50.7 | 0.0 | 50.7 | 51.4 | 0.0 | 51.2 | 0.2 | 0.8 | 2.2 | 51 | 7 | 5 | 99.98 | 93.75 |
| *No HWN* | | | | | | | | | | | | | | |
| Scenario 1 | 57.6 | 7.3 | 50.4 | 57.7 | 7.3 | 50.4 | 0.1 | 0.2 | 1.1 | 37 | 0 | 5 | 99.99 | 97.25 |
| Scenario 2 | 50.8 | 0.8 | 50.0 | 65.5 | 0.8 | 50.4 | 14.3 | 8.5 | 110.5 | 328 | 7 | 7 | 99.14 | 1.00 |
| Scenario 3 | 54.3 | 4.8 | 49.5 | 54.5 | 4.8 | 49.6 | 0.1 | 0.9 | 1.3 | 92 | 7 | 6 | 99.99 | 96.75 |
| Scenario 4 | 55.1 | 5.6 | 49.5 | 55.2 | 5.6 | 49.6 | 0.0 | 0.2 | 0.5 | 32 | 0 | 5 | 100.00 | 99.00 |
| *With HWN* | | | | | | | | | | | | | | |
| Scenario 1 | 55.4 | 8.9 | 46.5 | 55.4 | 8.9 | 46.5 | 0.1 | 0.6 | 0.5 | 55 | 5 | 7 | 100.00 | 98.75 |
| Scenario 2 | 48.2 | 1.6 | 46.6 | 65.0 | 1.6 | 46.9 | 16.5 | 10.4 | 151.9 | 542 | 7 | 6 | 98.81 | 1.25 |
| Scenario 3 | 51.4 | 5.5 | 45.9 | 51.4 | 5.5 | 45.9 | 0.0 | 0.2 | 0.7 | 36 | 0 | 5 | 99.99 | 98.00 |
| Scenario 4 | 52.0 | 6.2 | 45.8 | 52.1 | 6.2 | 45.8 | 0.1 | 0.4 | 0.6 | 39 | 0 | 6 | 100.00 | 97.50 |

- Scenario 2: This bare minimum investment scenario performs unsatisfactorily with very high expected penalty costs. The case without the HWN invests in a 35.4 t/h MP boiler compared to no boiler investments with the HWN.

  As a result of the very small operating reserves and lack of redundancy in steam generating equipments, the reliability of the steam networks are strongly impacted, leading to high penalty costs. The highest recorded number of shedding events in a single iteration was 542, leading to level 7 shedding at Site R and level 6 shedding in Site P.

  Figure 6.9 highlights the poor performance of this scenario. Despite the absence of investments, the penalty costs drive up with expected costs of this scenario, making it the most expensive and least reliable.

- Scenario 3: Despite the relatively high investment costs this scenario performs well, with very low penalty costs. It is the most promising investment strategy for the steam network given its high operability and comparatively low investment costs. Shedding events are slightly more frequent than those in Scenario 1 as the redundancy in equipments and installed capacity is lower.

  Figure 6.9 shows that the variation in costs for Scenario 3 is small. The solution without the HWN has more outliers in the costs and operability than that with the HWN.

- Scenario 4: This highly redundant investment strategy is the second most promising from a expected costs point of view. Its mean operability is higher than that of Scenario 3, though its operability threshold is lower when the HWN is included. This may be due to the lack of investment in symbiosis pipes, which increase the flexibility of networks.

The simulation results indicate that Scenario 3 and 4 permit highly resilient operations in the face of boiler failures. Scenario 4 has a slightly better operability than Scenario 3, which comes at an increased investment cost of $0.8 \times 10^6$ \$/yr without the HWN and $0.7 \times 10^6$ \$/yr with it.

Using the HWN reduces total expected costs significantly (approximately $3.0 \times 10^6$ \$/yr for scenarios 3 and 4), despite its $1.6 \times 10^6$ \$/yr required investment, while generally improving the operability of the system (except in Scenario 4).

From the results of the simulation, it can be recommended to use the investment strategy of Scenario 3 to identify replacements for the ageing CB boilers. The installation of the HWN can have significant benefits for the operability and costs of the cluster, though its installation will surely be quite disruptive.

## 6.5 Conclusion

Given the complexity of large steam network operations such as those in industrial sites and clusters, mathematical tools can be used to identify optimal operations and thereby drive down operational costs and fuel consumption, while providing better knowledge about the system.

By including load shedding formulations into these mathematical methods, this work has demonstrated that it is possible to limit the impacts of low operating reserves and undercapacity through optimised use of letdowns and load shedding. The optimal pathways for steam to reach consumers while limiting costs can be established in this way. This was achieved through a combination of penalty costs for PUs going offline and a load shedding order to prioritise deactivations.

These formulations were also shown to be highly effective in testing the feasibility of investment propositions stemming from TSAs.

Given the important impacts and non-negligible frequency of boiler failures, an algorithm was proposed to simulate steam boiler failures and quantify their impacts on the operability of steam networks. KPIs such as expected costs and operability of the networks were defined to judge the performance of networks facing boiler failures. In this way, the resilience of a steam network to boiler failures could be established.

The methods were applied to the Typical Industrial Cluster case study leading to the following findings.

- Optimised operations: The optimal operations of the TIC steam network under its current configuration were established. In this way, it was possible to show that through optimised use of the turbines a potential $3.8 \times 10^6$ \$/yr in costs reduction could be achieved.
- Load shedding: Optimal operations were established in the absence of the old CB boilers. As the overall demand of the cluster surpasses the installed steam generation capacity when the CB boilers are offline, load shedding was necessary though this was mitigated through an optimised use of the letdown desuperheaters.
- Hot Water Network feasibility: The TSA results identified a mean steam reduction potential of 74.3 t/h through the installation of the HWN. By including these modifications in the steam demand and optimising the operations, it was found that only a 52.4 t/h reduction in steam can be achieved due to the impacts on operations. In effect, by reducing the 5 barg steam consumption of Site P, excess steam was present on several occasions as a result of the high amount of cogeneration taking place. Consequently, this excess steam is vented to the atmosphere.

  These findings demonstrate the importance of combining conventional Energy Integration methods such as TSA and Pinch Analysis with advanced modelling and analysis to more accurately establish their impacts. Using mathematical optimisation techniques in the TSA could have increased the heat recovery potential of the HWN.
- Scenario generation: Through the use of the optimal operations and investment formulations, it was possible to generate a list of potential investments to replace the old CB boilers. 4 strategies were used, ranging from conservative (most expensive) to bare minimum investments (least expensive). The later included load shedding as a means of avoiding expensive investments. These 4 strategies were applied with and without the HWN, making 8 investment scenarios in total.

- Simulation of scenarios: The boiler failure simulation algorithm was applied to the current configuration (for reference) as well as the 8 proposed investments to identify their expected costs and resiliency to boiler failures.

  Results showed that by including boiler maintenance into the Scenario generation, highly resilient steam networks could be generated, providing sufficient oversizing and redundancy to overcome most boiler failures. As could be expected, bare minimum solutions performed very badly as too little overcapacity was present to deal with the boiler failures.

  The most promising results made use of a mix of technologies, including several boilers at different pressure levels and symbiosis pipes between both Sites. Including heat and power cogenerating turbines may have favoured the installation of more steam generation capacity, especially given the relatively high price of electricity used in the TIC case study.

Using mathematical optimisation to generate investment scenarios provided several highly resilient options. These were however not able to withstand each possible boiler failure configuration leading to necessary load shedding on some occasions. A computer aided methodology to identify optimally resilient investment strategies while minimising costs would be a welcome addition to the methodology.

This work also shown the benefits of cluster symbiosis as a means of reducing costs and operational problems. As the peak demand in steam is usually differed in industrial sites, common investments permit industrials to make use of each others available steam when necessary, increase the operability of the networks and help drive down investment costs.

Applying the principles developed in this chapter to other networks such can increase their understanding, reduce the costs and provide the tools for their management under constraint. For example, voluntary and optimised peak shaving in electricity networks could provide significant economic opportunities.

# 7 Conclusion and perspectives

*This chapter summarises the conclusions of the individual chapters of this thesis. Future improvements and applications of this work are discussed in the perspectives section.*

## 7.1 Conclusion

The consumption of energy in industrial sites has been estimated to be responsible for 39% of the 171.3 PWh of energy consumed worldwide in 2016 [109]. While reducing this energy consumption is a necessary step towards reaching the goals of the Paris Agreement [1], it also makes sense from an economic point of view as energy costs can be direct or indirect in the form of emissions taxes.

This thesis has aimed to identify pathways towards increased energy efficiency in the refining and petrochemical industries. These industries consume significant amounts of energy in the refining and crude oil and manufacture of high value chemicals. Combined to the chemical industry, these are estimated to be responsible for 9% of the overall worldwide energy consumptions [14].

Energy consumption takes place in many forms, though this thesis has particularly focused on steam. Steam is mainly generated in boilers and heat and power cogeneration units by combustion of fossil fuels. It is then dispatched into a steam network and consumed by processes. Given the scales at play, even an incremental reduction in steam consumption by these industries can have consequent impacts on GHG emissions and costs.

Reducing the consumption of steam can be achieved through several pathways:

1. Reduced steam demand of Process Units (PUs) as a result of improved heat integration.

2. Reduced energy demand of PUs as a result of improved conversion efficiency.

3. Reduced steam demand of industrial sites by improved integration.

The first point concerns the optimisation of recovery of heat and cooling inside PUs and has been extensively researched and applied to industry. The second point borders the domains of chemistry and energy. This work has focused on contributing to the third point, under the hypothesis that points 1 and 2 are already achieved. Improving integration of industrial sites and clusters implies creating synergies between PUs (through intermediate utility networks).

This thesis contributed to the domain by proposing a step-by-step methodology for the identification of energy efficiency solutions in the refining and petrochemical industries, while taking care to establish and ensure the operability of solutions identified through existing and novel techniques.

Chapters 2 to 4 covered the data collection, handling, validation and preparation for engineering studies, while Chapters 5 and 6 proposed methodologies to generate energy efficiency solutions and advanced analyses of their feasibilities and resilience.

Each step of the thesis was tested on the case study presented in Chapter 2, progressively building up towards resilient and practicable energy efficiency solutions in Chapter 6. The methods and results stemming from each chapter are briefly described below:

- **Chapter 2** presented the steam and cooling networks of a typical refining and petrochemical cluster, introducing readers to the particularities of these industries. The data assembled here demonstrated the complexity of such networks given the very large number of consumers and producers at multiple pressure levels and locations. The non-continuous nature of the thermodynamic properties such as flowrates further complicates these industrial sites.

  The data revealed that an important number of unmeasured thermodynamic properties in the networks (pressures, temperatures and flowrates) limit the global understanding of their operations and potential. For example losses in the form of steam leaks and condensation are ever present in such industries, though remain unquantified. Before any advanced energy efficiency study can be attempted, such issues need to be addressed.

  The cluster presented in this chapter constitutes the case study to be used in the remaining chapters to demonstrate the developed methods. As new investments in steam generation capacity are necessary, identifying energy efficient and resilient options becomes the final aim of the application of the methods to the data.

- **Chapter 3** proposed a methodology to improve data quality and quantify unknowns of the steam networks of refineries and petrochemical sites, with the aim of closing mass and energy balances in view of energy optimisation studies.

  An initial analysis of the data presented in Chapter 2 revealed that low measurement accuracy and unmeasured flowrates were equally to blame for open mass balances. Data Reconciliation was therefore chosen as the tool to improve data quality and calculate the unknowns.

  This Chapter did not present novel Data Reconciliation techniques, but rather applied the concepts to the refining and petrochemical industries, taking particular care to model previously unquantified properties, such as steam losses. In this way 17 typical types of common steam flows were defined and detailed to simplify the task of modelling the steam networks. The data to collect, their filtering algorithms as well as the Data Reconciliation parameters to apply to them were detailed.

The proposed methods were applied to the case study to close its mass balances. In doing so, the steam losses were calculated and shown to represent 5.7% of the overall steam consumption of the industrial cluster.

- **Chapter 4** detailed a computer aided algorithm to identify representative operating periods common to multiple data sets.

  Engineering studies rely on data to produce accurate and communicable results. Using mean values risks removing important information from the data as well as creating non-representative values. For this reason, scenario based approaches are typically chosen, though they may require important levels of process knowledge to create representative or normative scenarios.

  The proposed method uses a heuristic algorithm to identify an index of periods from which the representative scenarios can be extracted, without the need for advanced process knowledge. Periods of stability common to all data profiles are identified, as are key data properties such as their variations and periods where values are nil.

  As engineering studies such as Total Site Analyses (TSA) can be computationally and labour intensive, rather than using entire high resolution data sets, it is recommended to work with scenarios. This algorithm was therefore applied to the reconciled data of Chapter 3. The 365 daily averages of the 12 PUs were reduced to 19 representative scenarios which included the peak demand as well as most periods of PU shutdowns.

- **Chapter 5** presented a TSA methodology tuned to the refining and petrochemical industries. This included the data gathering and handling of the most frequently encountered process and utility streams, guided by graphical representations so as to facilitate the creation of the TSA results.

  Through a dual representation of the heat transfers, it was possible to reduce the overall data requirements significantly while ensuring the coherence of the results. Rigorous definitions of the utility requirements mean that site wide heating and cooling requirements were established.

  The methodology was applied to the 159 process streams and 13 turbines of the case study, using the reconciled data from Chapter 3 and the 19 periods identified in Chapter 4. A total of $41.1 \times 10^3$ data points were considered.

  The results of the TSA showed that a significant amount of heat recovery potential exists in the cluster, as the boilers supply 220.5 MW for heat exchange compared to a theoretical minimum of 37.0 MW. Given the low pinch point temperature that is typical of refining and petrochemical sites, this disparity can mostly be explained by the steam losses, tracing requirements and low temperature heat exchangers' use of 5 barg steam.

A Hot Water Network (HWN) was proposed with the potential to reduce the boiler outputs of the cluster by 15% (45.3 MW), through the installation of 15 new heat exchangers. However, the multi-period analysis of the solution revealed that further feasibility studies would be required to properly justify it as a solution, due to variations in its heat demand and supply.

- **Chapter 6** presented a methodology to optimise the operations of steam networks when available boiler supply is low. This was included into a simulation algorithm in which the impacts of boiler failures on operations could be measured. In this way, the expected costs and operability of networks and their investment propositions could be established.

  Given the high operating costs and emissions of utility networks, targeting and reaching their optimal operations can lead to significant benefits.

  Mathematical formulations exist to calculate optimal operations and size least costly investments. However, operability of such solutions can be questioned due to the variations in demand that are typical of industrial sites. To improve operability, a mathematical formulation for load shedding was introduced into the existing ones, to establish optimal operations of steam networks facing undercapacity or network disturbances. In this way, load shedding can also be proposed as an alternative to expensive investments.

  In order to determine the resilience of networks to disturbances such as failures, a simulation algorithm was then proposed. Though rare, such events have high impacts and do occasionally occur. Boilers were randomly shutoff to simulate their failures and the ability of the steam networks to overcome such events was tested. A number of key performance indicators related to operability and costs allowed for the resilience of utility networks to be calculated.

  The aim of the case study being to replace two ageing boilers, the proposed methodologies were applied to it in several steps:

  - Calculation of optimal operations: Costs could be reduced by 6.9% compared to actual values. This mostly stems from a better use of the steam turbines and translates to reduced national grid demand.

  - Calculation of optimal operations in the absence of the ageing boilers: Results indicated that a peak 124.5 t/h of load shedding in the petrochemical site would be required to overcome the lack of steam generation capacity. Yearly operational costs might be expected to increase by $3.0 \times 10^6$ \$/yr as a result of penalty costs and reduced turbine use.

  - Feasibility analysis of the HWN investment: Operational analysis of the HWN identified in Chapter 5 revealed that despite an estimated 45.3 MW reduction in total heating requirements, it is more likely that only 31.8 MW economies could be reached due to the network constraints. Steam would be required to supply a peak 27.8 MW of heat to the HWN due to imbalances in its supply and demand. The operations of the HWN were shown to decrease the steam boiler loads of the cluster by 10.7%.

- Generation of investment scenarios: 8 scenarios were identified to replace the ageing boilers, ranging from bare minimum solutions to high redundancy solutions. These also included symbiosis propositions for the cluster by sharing steam between the sites.

- Simulation of investment scenarios to determine their resilience: Results showed that scenarios generated with maintenance in mind automatically provided enough redundancy and oversizing to overcome the majority of boiler failures. Scenarios generated to only minimise costs performed very poorly and led to high penalty costs as a result of boiler failures. The HWN was shown to contribute towards resiliency and reduced costs.

  Final solutions indicated that a mix of steam sharing symbiosis pipes, a medium and a high pressure boiler and the HWN provided highly resilient operations to the steam network at lowest investment operational costs.

This thesis has presented the particularities of utility networks in the refining and petrochemical industries. The data to be collected as well as methodologies to improve its quality and optimally reduce its resolution permitted for advanced Energy Integration and efficiency solutions to be generated.

A methodology for the application of TSAs to the refining and petrochemical industry was detailed so as to simplify these complex studies. Steam network optimisation and simulation algorithms were developed to provide the possibility to test solutions generated by TSAs or other methods and determine their resilience to perturbatory events.

The methods were systematically applied to a case study with the aim of guiding engineers from the data collection to the final solutions, backed up with metrics to justify their feasibility to decision makers.

## 7.2 Perspectives

Energy sources such as fossil fuels enable for work to be done at an incredible level, though much of it is wasted. Reduction in energy consumption should not deprive us of this power. This work has shown that for the refining and petrochemical industries, substantial reductions in emissions and costs can be achieved through better use of available resources.

As a result of the European Energy Efficiency Directive (EED) implemented in 2012, which aims to reduce energy consumption by 20% by 2020, mandatory energy audits are likely to be the most significant driver of energy efficiency studies in the years to come. As data collection and validation are a necessary and highly laborious part of any energy audit or efficiency study, their facilitation is key. The first two chapters focussed on such questions, though substantially more could be done to clearly define the data requirements of such works as well as how to validate them with performance indicators. This data is required for all efficiency studies but also for monitoring in general, leading to a deeper understanding of system performance as well as better forecasts.

Identifying that the minimum theoretical energy targets of industrial clusters can be lower than 20% of the actual consumption when resources are pooled through symbiosis, without even considering PU Process Integration or future technological accomplishments, makes the task of reaching our climate goals much less impossible than previously believed.

The methodologies used to generate solutions for the case study did not take full advantage of the extensive works already carried out in the field of Energy Integration. They would have strongly benefited from the inclusion of optimally placed utility networks, cogeneration devices, heat-pumps and other heat recovery devices. No barriers exist to the integration of previously developed methods into this thesis.

A major assumption of this work has been that PU operations and their thermal exchanges have already been optimised from an energy perspective. This was necessary to limit the scope of the work, though it is often not the case. Furthermore, important technological limitations exist from a chemical point of view for example by improved separation of refining products or more efficient catalysts in petrochemistry. The true potential for reduced fossil fuel consumption in these industries must be addressed from bottom-up and top-down simultaneously.

The analysis of solutions in this work were performed using a multi-period approach. It was demonstrated that large systems must be considered in this way to avoid producing undersized or infeasible solutions. Thanks to advances in computing power, it is now possible to carry out large multi-period optimisation studies to produce feasible and practicable results.

Engineers must be provided the tools to design heat-exchange networks and utility systems that minimise energy consumption. By designing user-friendly and automated tools to apply methods such as those presented in this work, or optimal heat-exchanger design methodologies [108, 85] significant progress could be achieved.

Even with such tools, the penetration of Energy Integration solutions will depend on the skills and knowledge of the engineers employing them. As these methods are fairly complex they may be unsuitable for process engineers in small industrial sites where they will be seldom applied. Such engineers typically focus on optimisation studies relating to day-to-day operations rather infrastructure projects. Larger companies with central engineering or internal consulting services should assuredly develop these advanced competences so as to provide punctual services relating to infrastructure modifications, especially at times of retrofit or investments in new systems.

This work has focussed on steam as a key energy vector in the chemical industry. Further work should be extended to electricity networks as well as other significant ones such as hydrogen, nitrogen networks and fuel gas and methane networks. Petrochemical and refining sites often share space within clusters, as do chemical plants in general. In electricity networks, voluntary and optimised peak shaving in industry with the aim of reducing national demand could provide significant economic opportunities.

Extending this work to other sectors of the chemical industry as well as other industries such as pulp and paper or metallurgy may offer significant potential for energy savings. A holistic view of industrial energy resources and the potential for thermo-environomic symbiosis would greatly benefit advances towards a circular economy, for example through the recycling of low temperature waste heat in district heating solutions for communities near industrial sites.

# A Process Units

The steam networks, steam demand, aero-cooling and water-cooling demands of the units of Sites R and P are presented below. The steam properties are reconciled while the aero-cooling and water-cooling are not. All process data is also available online at [53].

The tables present steam demand, therefore negative values indicate a net import of steam while positive values correspond to what is imported by the Process Units (PUs) from the utility network. Similarly negative heat exchanges correspond to steam generation.

## A.1 Site R Process Units

All process requirements are defined using True Boiling Point definitions shown in Tables A.7, A.8 and A.9. For injections, the pressure of the columns are given. This pressure can be used to calculate the minimum injection pressure of the steam.

Turbine isentropic efficiencies are also supplied so as to calculate the steam cogeneration. Their overview is presented in Table A.10.

Losses in the process units of Site R correspond to real physical losses as well as the remains of unexplained steam consumption.

## Unit A – Separation

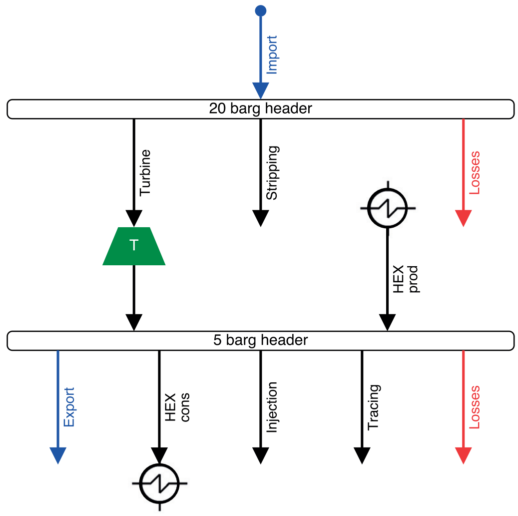



Figure A.1 – Schematic of the steam network of Site R Unit A.

Table A.1 – Steam, cooling demand and mean thermodynamic properties for Site R Unit A.

| Level [barg] | Type | Function | Flowrate [t/h] Mean | Flowrate [t/h] Max | Power [MW] Mean | Power [MW] Max | Process [°C] $T_{in}$ | Process [°C] $T_{out}$ | Column [barg] | $\eta$ [%] |
|---|---|---|---|---|---|---|---|---|---|---|
| 20 | Import | | -10.8 | -20.2 | -6.2 | -11.5 | | | | |
| 20 | Turbine | Turbo pumps | 7.3 | 14.1 | 4.2 | 8.1 | | | | 30.0 |
| 20 | Stripping | | 2.5 | 4.0 | 1.4 | 2.3 | | | 9.0 | |
| 20 | Losses | | 1.0 | 4.0 | 0.6 | 2.3 | | | | |
| | **Total cons.** | | **10.8** | **20.2** | **6.2** | **11.5** | | | | |
| 5 | HEX | Condensation | -5.3 | -6.9 | -3.2 | -4.2 | 220 | 205 | | |
| 5 | Export | | 4.1 | 10.4 | 2.5 | 6.3 | | | | |
| 5 | HEX | Heating | 5.0 | 16.9 | 3.0 | 10.2 | 110 | 150 | | |
| 5 | Injection | | 0.9 | 1.2 | 0.5 | 0.7 | | | 0.4 | |
| 5 | Tracing | Storage tanks | 2.0 | 2.7 | 1.2 | 1.6 | 90 | 105 | | |
| 5 | Losses | | 0.5 | 0.7 | 0.3 | 0.4 | | | | |
| | **Total cons.** | | **12.6** | **20.6** | **7.6** | **12.4** | | | | |
| | Aero cooling | Cooling | | | 19.1 | 28.7 | 150 | 110 | | |
| | Water cooling | Cooling | | | 5.3 | 8.1 | 100 | 60 | | |

## Unit B – Isomerisation

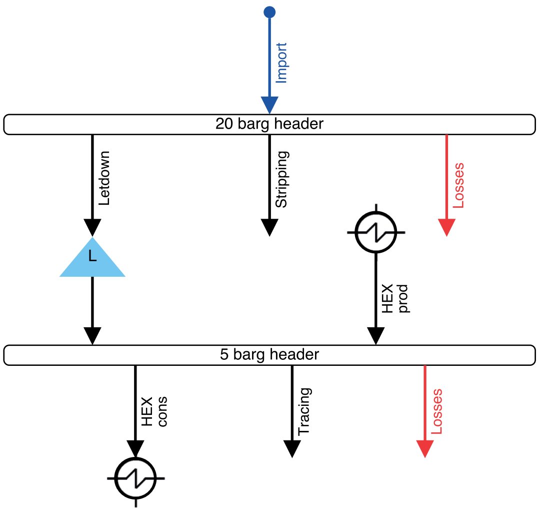



Figure A.2 – Schematic of the steam network of Site R Unit B.

Table A.2 – Steam, cooling demand and mean thermodynamic properties for Site R Unit B.

| Level [barg] | Type | Function | Flowrate [t/h] Mean | Flowrate [t/h] Max | Power [MW] Mean | Power [MW] Max | Process [°C] $T_{in}$ | Process [°C] $T_{out}$ | Column [barg] | $\eta$ [%] |
|---|---|---|---|---|---|---|---|---|---|---|
| 20 | Import | | -10.2 | -16.5 | -5.8 | -9.4 | | | | |
| 20 | HEX | Evaporation | 6.2 | 11.5 | 3.6 | 6.6 | 170 | 190 | | |
| 20 | Injection | | 1.2 | 1.5 | 0.7 | 0.9 | | | 5.2 | |
| 20 | Letdown | | 2.0 | 5.7 | 1.2 | 3.3 | | | | |
| 20 | Losses | | 0.8 | 1.2 | 0.5 | 0.7 | | | | |
| | **Total cons.** | | **10.2** | **16.5** | **5.8** | **9.4** | | | | |
| 5 | HEX | Cooling | -5.1 | -6.3 | -3.1 | -3.8 | 210 | 187 | | |
| 5 | HEX | Evaporation | 5.7 | 9.6 | 3.5 | 5.8 | 115 | 125 | | |
| 5 | Losses | | 0.5 | 0.5 | 0.3 | 0.3 | | | | |
| 5 | Tracing | Pipe tracing | 0.9 | 1.0 | 0.5 | 0.6 | 90 | 105 | | |
| | **Total cons.** | | **7.1** | **11.0** | **4.3** | **6.6** | | | | |
| | Aero cooling | Cooling | | | 7.3 | 10.8 | 150 | 110 | | |
| | Water cooling | Cooling | | | 5.4 | 7.8 | 100 | 60 | | |

## Unit C – Hydrogenation

**Comments:** Turbines used to compress gases. Reactors produce superheated steam.

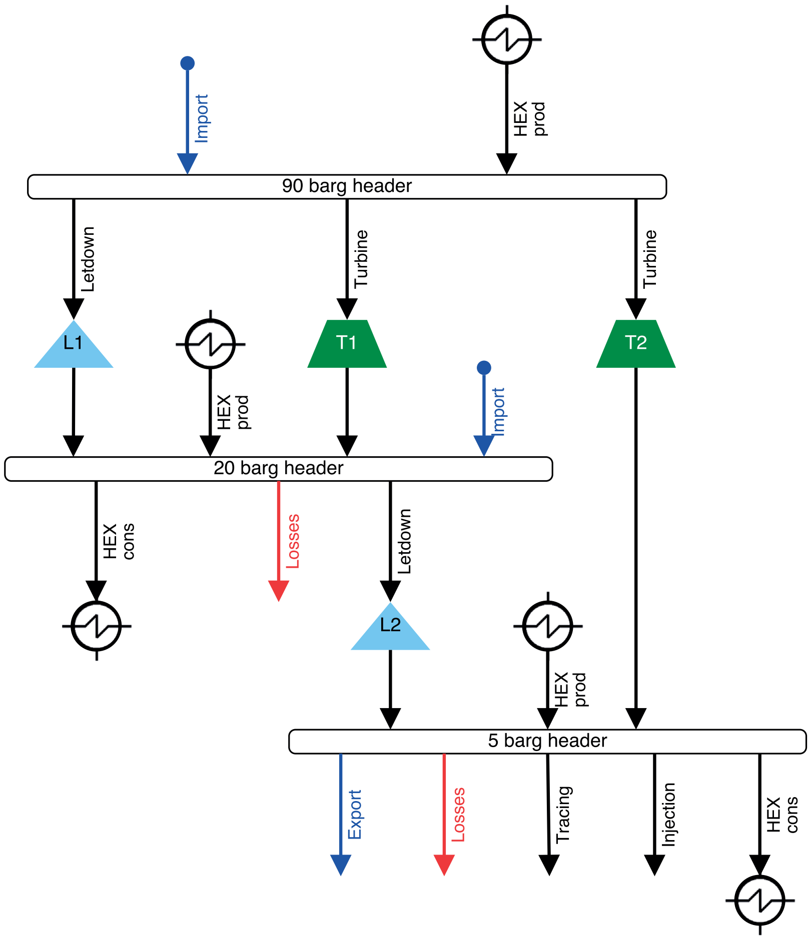



Figure A.3 – Schematic of the steam network of Site R Unit C.

Table A.3 – Steam, cooling demand and mean thermodynamic properties for Site R Unit C.

| Level [barg] | Type | Function | Flowrate [t/h] Mean | Flowrate [t/h] Max | Power [MW] Mean | Power [MW] Max | Process [°$C$] $T_{in}$ | Process [°$C$] $T_{out}$ | Column [barg] | $\eta$ [%] |
|---|---|---|---|---|---|---|---|---|---|---|
| 90 | Import | | -13.4 | -22.7 | -7.3 | -12.4 | | | | |
| 90 | HEX | Reactor cooling | -8.5 | -14.3 | -4.7 | -7.8 | 550 | 500 | | |
| 90 | Turbine T1 | | 9.1 | 18.8 | 5.0 | 10.3 | | | | 40.0 |
| 90 | Turbine T2 | | 11.9 | 14.5 | 6.5 | 7.9 | | | | 40.0 |
| 90 | Letdown L1 | | 1.0 | 2.1 | 0.5 | 1.1 | | | | |
| | **Total cons.** | | **21.9** | **31.4** | **12.0** | **17.2** | | | | |
| 20 | Import | | -8.9 | -19.3 | -5.1 | -11.1 | | | | |
| 20 | HEX | | -6.0 | -31.5 | -3.5 | -18.0 | 600 | 600 | | |
| 20 | HEX | Heating | 21.2 | 31.9 | 12.1 | 18.2 | 150 | 200 | | |
| 20 | Losses | | 0.9 | 1.3 | 0.5 | 0.7 | 375 | 375 | | |
| 20 | Letdown L2 | | 2.9 | 17.9 | 1.6 | 10.2 | | | | |
| | **Total cons.** | | **25.0** | **36.3** | **14.3** | **20.7** | | | | |
| 5 | HEX | Cooling | -7.5 | -20.7 | -4.5 | -12.5 | 350 | 300 | | |
| 5 | Export | | 12.9 | 28.3 | 7.8 | 17.1 | | | | |
| 5 | HEX | Condensation | 3.7 | 28.3 | 2.2 | 17.1 | 75 | 115 | | |
| 5 | Injection | | 2.0 | 2.8 | 1.2 | 1.7 | | | 1.0 | |
| 5 | Losses | | 1.2 | 1.7 | 0.7 | 1.1 | | | | |
| 5 | Tracing | | 2.5 | 4.0 | 1.5 | 2.4 | 90 | 105 | | |
| | **Total cons.** | | **22.3** | **36.1** | **13.4** | **21.8** | | | | |
| | Aero cooling | Cooling | | | 15.0 | 22.5 | 140 | 85 | | |
| | Water cooling | Cooling | | | 8.8 | 18.4 | 125 | 65 | | |

## Unit D – Cracker

**Comments:** Turbines used for turbo pumps. Reactors produce superheated steam.

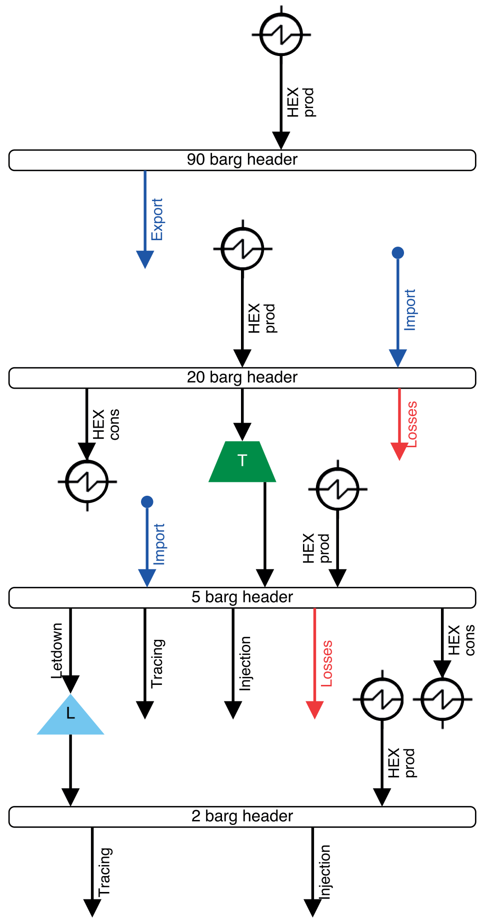



Figure A.4 – Schematic of the steam network of Site R Unit D.

Table A.4 – Steam, cooling demand and mean thermodynamic properties for Site R Unit D.

| Level [barg] | Type | Function | Flowrate [t/h] Mean | Flowrate [t/h] Max | Power [MW] Mean | Power [MW] Max | Process [°C] $T_{in}$ | Process [°C] $T_{out}$ | Column [barg] | $\eta$ [%] |
|---|---|---|---|---|---|---|---|---|---|---|
| 90 | Export | | -12.8 | -20.4 | -7.0 | -11.1 | | | | |
| 90 | HEX | Catalyser cooling | 12.8 | 20.4 | 7.0 | 11.1 | 615 | 615 | | |
| | **Total cons.** | | **12.8** | **20.4** | **7.0** | **11.1** | | | | |
| 20 | Import | | -7.5 | -18.0 | -4.3 | -10.3 | | | | |
| 20 | HEX | Condensation | -10.1 | -12.2 | -5.8 | -7.0 | 315 | 290 | | |
| 20 | HEX | Heating | 16.1 | 29.5 | 9.2 | 16.9 | 125 | 180 | | |
| 20 | Losses | | 0.5 | 0.6 | 0.3 | 0.3 | | | | |
| 20 | Turbine | | 0.9 | 8.8 | 0.5 | 5.0 | | | | 30.0 |
| | **Total cons.** | | **17.6** | **30.0** | **10.0** | **17.2** | | | | |
| 5 | Import | | -8.2 | -18.6 | -4.9 | -11.2 | | | | |
| 5 | HEX | Condensation | -4.9 | -18.6 | -3.0 | -11.2 | 204 | 197 | | |
| 5 | HEX | Evaporation | 8.2 | 28.9 | 4.9 | 17.4 | 125 | 125 | | |
| 5 | Injection | | 1.4 | 2.2 | 0.8 | 1.3 | | | 1.5 | |
| 5 | Letdown | | 1.9 | 3.4 | 1.1 | 2.1 | | | | |
| 5 | Losses | | 0.4 | 0.7 | 0.2 | 0.4 | | | | |
| 5 | Tracing | Tank heating | 2.1 | 3.6 | 1.3 | 2.2 | 90 | 105 | | |
| | **Total cons.** | | **14.0** | **34.9** | **8.4** | **21.1** | | | | |
| 2 | HEX | Condensation | -1.4 | -2.3 | -0.9 | -1.5 | 180 | 180 | | |
| 2 | Injection | | 0.8 | 1.5 | 0.5 | 0.9 | | | -0.6 | |
| 2 | Tracing | Pipe tracing | 2.5 | 4.3 | 1.6 | 2.7 | 60 | 85 | | |
| | **Total cons.** | | **3.3** | **5.3** | **2.1** | **3.3** | | | | |
| | Aero cooling | Cooling | | | 6.2 | 15.8 | 180 | 80 | | |
| | Water cooling | Cooling | | | 9.0 | 26.2 | 130 | 65 | | |

## Unit E – Separation

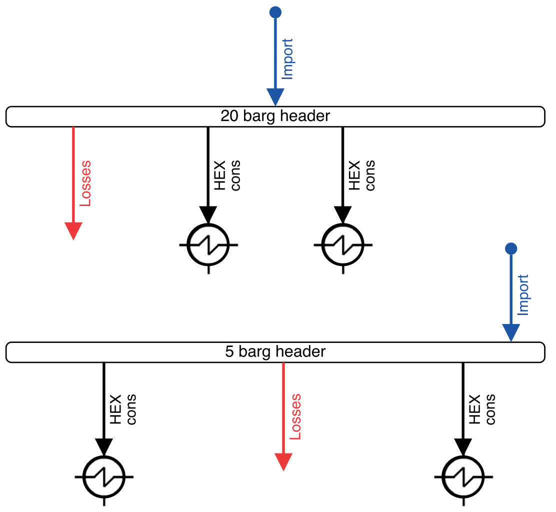



Figure A.5 – Schematic of the steam network of Site R Unit E.

Table A.5 – Steam, cooling demand and mean thermodynamic properties for Site R Unit E.

| Level [barg] | Type | Function | Flowrate [t/h] Mean | Flowrate [t/h] Max | Power [MW] Mean | Power [MW] Max | Process [°C] $T_{in}$ | Process [°C] $T_{out}$ | Column [barg] | $\eta$ [%] |
|---|---|---|---|---|---|---|---|---|---|---|
| 20 | Import | | -19.7 | -27.7 | -11.3 | -15.9 | | | | |
| 20 | HEX | Evaporation | 5.8 | 7.8 | 3.3 | 4.5 | 160 | 190 | | |
| 20 | HEX | Heating | 13.2 | 21.4 | 7.5 | 12.3 | 120 | 170 | | |
| 20 | Losses | | 0.8 | 1.2 | 0.4 | 0.7 | | | | |
| | **Total cons.** | | **19.7** | **27.7** | **11.3** | **15.9** | | | | |
| 5 | Import | | -13.4 | -19.5 | -8.1 | -11.8 | | | | |
| 5 | HEX | Evaporation | 4.0 | 5.3 | 2.4 | 3.2 | 115 | 115 | | |
| 5 | HEX | Heating | 8.6 | 14.9 | 5.2 | 9.0 | 90 | 100 | | |
| 5 | Losses | | 0.7 | 1.5 | 0.4 | 0.9 | | | | |
| | **Total cons.** | | **13.4** | **19.5** | **8.1** | **11.8** | | | | |
| | Aero cooling | Cooling | | | 3.8 | 5.2 | 150 | 95 | | |
| | Water cooling | Cooling | | | 7.2 | 14.9 | 110 | 65 | | |

### Unit F – Purification

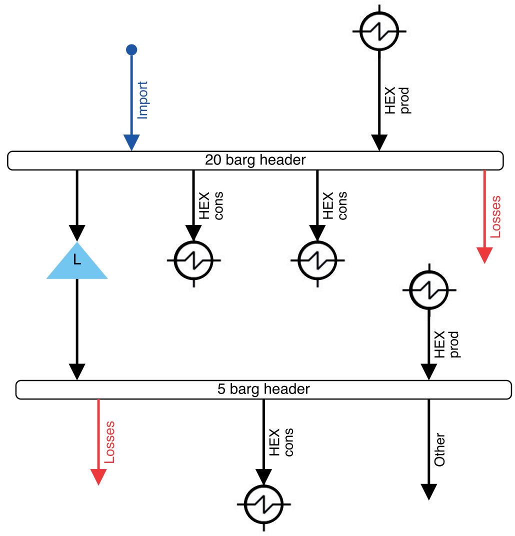



Figure A.6 – Schematic of the steam network of Site R Unit F.

Table A.6 – Steam, cooling demand and mean thermodynamic properties for Site R Unit F.

| Level [barg] | Type | Function | Flowrate [t/h] Mean | Flowrate [t/h] Max | Power [MW] Mean | Power [MW] Max | Process [°C] $T_{in}$ | Process [°C] $T_{out}$ | Column [barg] | $\eta$ [%] |
|---|---|---|---|---|---|---|---|---|---|---|
| 20 | Import | | -15.8 | -27.3 | -9.0 | -15.6 | | | | |
| 20 | HEX | Evaporation | 5.7 | 9.3 | 3.3 | 5.3 | 175 | 175 | | |
| 20 | HEX | Heating | 7.7 | 22.1 | 4.4 | 12.6 | 160 | 190 | | |
| 20 | Letdown | | 2.6 | 7.2 | 1.5 | 4.1 | | | | |
| 20 | Losses | | 1.0 | 1.8 | 0.6 | 1.0 | | | | |
| 20 | HEX | Condensation | -1.3 | -2.4 | -0.7 | -1.3 | 325 | 295 | | |
| | **Total cons.** | | **17.1** | **28.4** | **9.8** | **16.3** | | | | |
| 5 | HEX | Condensation | -3.9 | -7.3 | -2.3 | -4.4 | 218 | 217 | | |
| 5 | HEX | Evaporation | 3.7 | 6.5 | 2.2 | 3.9 | 116 | 134 | | |
| 5 | Losses | | 1.1 | 2.0 | 0.7 | 1.2 | | | | |
| 5 | Other | | 1.5 | 3.1 | 0.9 | 1.9 | | | | |
| | **Total cons.** | | **6.4** | **10.7** | **3.8** | **6.5** | | | | |
| | Aero cooling | Cooling | | | 0.0 | 0.0 | 140 | 85 | | |
| | Water cooling | Cooling | | | 12.4 | 18.4 | 100 | 65 | | |

Table A.7 – Mean hot and cold stream data for Site Site R.

| Name | Type | P | $T_1$ | $Q_1$ | $T_2$ | $Q_2$ | $T_3$ | $Q_3$ | $T_4$ | $Q_4$ | $T_5$ | $Q_5$ | $T_6$ | $Q_6$ | $T_7$ | $Q_7$ | $T_8$ | $Q_8$ | $T_9$ | $Q_9$ | $T_{10}$ | $Q_{10}$ | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| S1A MP strip | Cons | 21 | 180 | 1.4 | 180 | | | | | | | | | | | | | | | | | | |
| S1A MP loss | Cons | 21 | 25 | 0.6 | 26 | | | | | | | | | | | | | | | | | | |
| S1A BP inj | Cons | 6 | 110 | 0.5 | 110 | | | | | | | | | | | | | | | | | | |
| S1A BP trac | Cons | 6 | 65 | 1.1 | 65 | | | | | | | | | | | | | | | | | | |
| S1A BP loss | Cons | 6 | 25 | 0.3 | 26 | | | | | | | | | | | | | | | | | | |
| S1A BP chex | Cons | 6 | 63 | 0.8 | 63 | 0.8 | 110 | 1.5 | 112 | | | | | | | | | | | | | | |
| S1A BP phex | Prod | 6 | 220 | 1.0 | 210 | 2.2 | 205 | | | | | | | | | | | | | | | | |
| S1A AERO1 | Aero | | 153 | 0.5 | 132 | 0.5 | 123 | 0.5 | 118 | 0.5 | 114 | 0.5 | 108 | 0.5 | 99 | 0.5 | 95 | 0.5 | 86 | 0.5 | 75 | 0.5 | 53 |
| S1A AERO2 | Aero | | 148 | 0.4 | 138 | 0.4 | 134 | 0.4 | 128 | 0.4 | 124 | 0.4 | 119 | 0.4 | 114 | 0.4 | 104 | 0.4 | 94 | 0.4 | 78 | 0.4 | 54 |
| S1A AERO3 | Aero | | 130 | 0.5 | 120 | 0.5 | 114 | 0.5 | 113 | 0.5 | 104 | 0.5 | 100 | 0.5 | 93 | 0.5 | 84 | 0.5 | 61 | | | | |
| S1A AERO3 bis | Aero | | 178 | 0.5 | 152 | 0.5 | 130 | | | | | | | | | | | | | | | | |
| S1A AERO4 | Aero | | 146 | 0.4 | 139 | 0.4 | 133 | 0.4 | 125 | 0.4 | 112 | 0.4 | 106 | 0.4 | 93 | 0.4 | 77 | 0.4 | 46 | | | | |
| S1A AERO4 bis | Aero | | 189 | 0.4 | 160 | 0.4 | 146 | | | | | | | | | | | | | | | | |
| S1A AERO5 | Aero | | 75 | 0.1 | 69 | 0.1 | 66 | 0.1 | 64 | 0.1 | 63 | 0.1 | 62 | 0.1 | 59 | 0.1 | 58 | 0.1 | 55 | 0.1 | 52 | 0.1 | 45 |
| S1A CW1 | CW | | 145 | 0.2 | 143 | 0.2 | 142 | 0.2 | 141 | 0.2 | 141 | 0.2 | 141 | 0.2 | 141 | 0.2 | 140 | 0.2 | 140 | 0.2 | 139 | 0.2 | 138 |
| S1A CW2 | CW | | 65 | 0.0 | 40 | | | | | | | | | | | | | | | | | | |
| S1A CW3 | CW | | 181 | 0.3 | 178 | 0.3 | 175 | 0.3 | 167 | | | | | | | | | | | | | | |
| S1A CW3 bis | CW | | 208 | 0.3 | 199 | 0.3 | 191 | 0.3 | 188 | 0.3 | 186 | 0.3 | 185 | 0.3 | 182 | 0.3 | 181 | | | | | | |
| S1B MP inj | Cons | 21 | 160 | 0.5 | 160 | | | | | | | | | | | | | | | | | | |
| S1B MP chex | Cons | 21 | 170 | 0.9 | 170 | 1.5 | 180 | 0.6 | 190 | | | | | | | | | | | | | | |
| S1B MP loss | Cons | 21 | 25 | 0.5 | 26 | | | | | | | | | | | | | | | | | | |
| S1B BP phex | Prod | 6 | 210 | 0.2 | 200 | 0.5 | 195 | 0.7 | 191 | 1.0 | 189 | | | | | | | | | | | | |
| S1B BP trac | Cons | 6 | 85 | 0.5 | 85 | | | | | | | | | | | | | | | | | | |
| S1B BP loss | Cons | 6 | 25 | 0.3 | 26 | | | | | | | | | | | | | | | | | | |
| S1B BP chex | Cons | 6 | 115 | 2.8 | 115 | 0.7 | 125 | | | | | | | | | | | | | | | | |
| S1B AERO1 | Aero | | 78 | 3.6 | 45 | | | | | | | | | | | | | | | | | | |
| S1B AERO2 | Aero | | 70 | 1.9 | 45 | | | | | | | | | | | | | | | | | | |
| S1B AERO3 | Aero | | 59 | 1.8 | 45 | | | | | | | | | | | | | | | | | | |
| S1B CW1 | CW | | 94 | 2.7 | 34 | | | | | | | | | | | | | | | | | | |
| S1B CW2 | CW | | 120 | 2.6 | 29 | | | | | | | | | | | | | | | | | | |
| S1C HP phex | Prod | 90 | 550 | 3.2 | 550 | 3.2 | 500 | | | | | | | | | | | | | | | | |
| S1C MP loss | Prod | 90 | 25 | 0.5 | 26 | | | | | | | | | | | | | | | | | | |
| S1C MP chex | Cons | 21 | 150 | 2.3 | 160 | 2.3 | 170 | 2.3 | 180 | 3.5 | 190 | 1.2 | 200 | | | | | | | | | | |
| S1C MP phex | Prod | 21 | 600 | 3.2 | 600 | | | | | | | | | | | | | | | | | | |
| S1C BP inj | Cons | 6 | 120 | 1.3 | 120 | | | | | | | | | | | | | | | | | | |
| S1C BP loss | Cons | 6 | 25 | 0.7 | 26 | | | | | | | | | | | | | | | | | | |
| S1C BP trac | Cons | 6 | 75 | 1.8 | 75 | | | | | | | | | | | | | | | | | | |
| S1C BP chex | Cons | 6 | 75 | 0.4 | 80 | 0.7 | 80 | 0.7 | 115 | | | | | | | | | | | | | | |
| S1C BP phex | Prod | 6 | 350 | 1.0 | 340 | 0.5 | 330 | 0.8 | 320 | 1.6 | 310 | 1.0 | 305 | 0.3 | 300 | | | | | | | | |
| S1A MP strip | Cons | 21 | 180 | 1.4 | 180 | | | | | | | | | | | | | | | | | | |
| S1A MP loss | Cons | 21 | 25 | 0.6 | 26 | | | | | | | | | | | | | | | | | | |
| S1A BP inj | Cons | 6 | 110 | 0.5 | 110 | | | | | | | | | | | | | | | | | | |
| S1A BP trac | Cons | 6 | 65 | 1.1 | 65 | | | | | | | | | | | | | | | | | | |
| S1A BP loss | Cons | 6 | 25 | 0.3 | 26 | | | | | | | | | | | | | | | | | | |
| S1A BP chex | Cons | 6 | 63 | 0.8 | 63 | 0.8 | 110 | 1.5 | 112 | | | | | | | | | | | | | | |
| S1A BP phex | Prod | 6 | 220 | 1.0 | 210 | 2.2 | 205 | | | | | | | | | | | | | | | | |

Table A.8 – Mean hot and cold stream data for Site Site R.

| Name | Type | P | $T_1$ | $Q_1$ | $T_2$ | $Q_2$ | $T_3$ | $Q_3$ | $T_4$ | $Q_4$ | $T_5$ | $Q_5$ | $T_6$ | $Q_6$ | $T_7$ | $Q_7$ | $T_8$ | $Q_8$ | $T_9$ | $Q_9$ | $T_{10}$ | $Q_{10}$ | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| S1A AERO1 | Aero | | 153 | 0.5 | 132 | 0.5 | 123 | 0.5 | 118 | 0.5 | 114 | 0.5 | 108 | 0.5 | 99 | 0.5 | 95 | 0.5 | 86 | 0.5 | 75 | 0.5 | 53 |
| S1A AERO2 | Aero | | 148 | 0.4 | 138 | 0.4 | 134 | 0.4 | 128 | 0.4 | 124 | 0.4 | 119 | 0.4 | 114 | 0.4 | 104 | 0.4 | 94 | 0.4 | 78 | 0.4 | 54 |
| S1A AERO3 | Aero | | 130 | 0.5 | 120 | 0.5 | 114 | 0.5 | 113 | 0.5 | 104 | 0.5 | 100 | 0.5 | 93 | 0.5 | 84 | 0.5 | 61 | | | | |
| S1A AERO3 bis | Aero | | 178 | 0.5 | 152 | 0.5 | 130 | | | | | | | | | | | | | | | | |
| S1A AERO4 | Aero | | 146 | 0.4 | 139 | 0.4 | 133 | 0.4 | 125 | 0.4 | 112 | 0.4 | 106 | 0.4 | 93 | 0.4 | 77 | 0.4 | 46 | | | | |
| S1A AERO4 bis | Aero | | 189 | 0.4 | 160 | 0.4 | 146 | | | | | | | | | | | | | | | | |
| S1A AERO5 | Aero | | 75 | 0.1 | 69 | 0.1 | 66 | 0.1 | 64 | 0.1 | 63 | 0.1 | 62 | 0.1 | 59 | 0.1 | 58 | 0.1 | 55 | 0.1 | 52 | 0.1 | 45 |
| S1A CW1 | CW | | 145 | 0.2 | 143 | 0.2 | 142 | 0.2 | 141 | 0.2 | 141 | 0.2 | 141 | 0.2 | 141 | 0.2 | 140 | 0.2 | 140 | 0.2 | 139 | 0.2 | 138 |
| S1A CW2 | CW | | 65 | 0.0 | 40 | | | | | | | | | | | | | | | | | | |
| S1A CW3 | CW | | 181 | 0.3 | 178 | 0.3 | 175 | 0.3 | 167 | | | | | | | | | | | | | | |
| S1A CW3 bis | CW | | 208 | 0.3 | 199 | 0.3 | 191 | 0.3 | 188 | 0.3 | 186 | 0.3 | 185 | 0.3 | 182 | 0.3 | 181 | | | | | | |
| S1B MP inj | Cons | 21 | 160 | 0.5 | 160 | | | | | | | | | | | | | | | | | | |
| S1B MP chex | Cons | 21 | 170 | 0.9 | 170 | 1.5 | 180 | 0.6 | 190 | | | | | | | | | | | | | | |
| S1B MP loss | Cons | 21 | 25 | 0.5 | 26 | | | | | | | | | | | | | | | | | | |
| S1B BP phex | Prod | 6 | 210 | 0.2 | 200 | 0.5 | 195 | 0.7 | 191 | 1.0 | 189 | | | | | | | | | | | | |
| S1B BP trac | Cons | 6 | 85 | 0.5 | 85 | | | | | | | | | | | | | | | | | | |
| S1B BP loss | Cons | 6 | 25 | 0.3 | 26 | | | | | | | | | | | | | | | | | | |
| S1B BP chex | Cons | 6 | 115 | 2.8 | 115 | 0.7 | 125 | | | | | | | | | | | | | | | | |
| S1B AERO1 | Aero | | 78 | 3.6 | 45 | | | | | | | | | | | | | | | | | | |
| S1B AERO2 | Aero | | 70 | 1.9 | 45 | | | | | | | | | | | | | | | | | | |
| S1B AERO3 | Aero | | 59 | 1.8 | 45 | | | | | | | | | | | | | | | | | | |
| S1B CW1 | CW | | 94 | 2.7 | 34 | | | | | | | | | | | | | | | | | | |
| S1B CW2 | CW | | 120 | 2.6 | 29 | | | | | | | | | | | | | | | | | | |
| S1C HP phex | Prod | 90 | 550 | 3.2 | 550 | 3.2 | 500 | | | | | | | | | | | | | | | | |
| S1C MP loss | Prod | 90 | 25 | 0.5 | 26 | | | | | | | | | | | | | | | | | | |
| S1C MP chex | Cons | 21 | 150 | 2.3 | 160 | 2.3 | 170 | 2.3 | 180 | 3.5 | 190 | 1.2 | 200 | | | | | | | | | | |
| S1C MP phex | Prod | 21 | 600 | 3.2 | 600 | | | | | | | | | | | | | | | | | | |
| S1C BP inj | Cons | 6 | 120 | 1.3 | 120 | | | | | | | | | | | | | | | | | | |
| S1C BP loss | Cons | 6 | 25 | 0.7 | 26 | | | | | | | | | | | | | | | | | | |
| S1C BP trac | Cons | 6 | 75 | 1.8 | 75 | | | | | | | | | | | | | | | | | | |
| S1C BP chex | Cons | 6 | 75 | 0.4 | 80 | 0.7 | 80 | 0.7 | 115 | | | | | | | | | | | | | | |
| S1C BP phex | Prod | 6 | 350 | 1.0 | 340 | 0.5 | 330 | 0.8 | 320 | 1.6 | 310 | 1.0 | 305 | 0.3 | 300 | | | | | | | | |
| S1C AERO1 | Aero | | 168 | 2.2 | 120 | | | | | | | | | | | | | | | | | | |
| S1C AERO2 | Aero | | 214 | 4.3 | 140 | | | | | | | | | | | | | | | | | | |
| S1C AERO3 | Aero | | 79 | 3.1 | 50 | | | | | | | | | | | | | | | | | | |
| S1C AERO4 | Aero | | 157 | 5.3 | 120 | | | | | | | | | | | | | | | | | | |
| S1C CW1 | CW | | 120 | 0.8 | 33 | | | | | | | | | | | | | | | | | | |
| S1C CW2 | CW | | 140 | 2.4 | 94 | | | | | | | | | | | | | | | | | | |
| S1C CW3 | CW | | 50 | 2.0 | 41 | | | | | | | | | | | | | | | | | | |
| S1C CW4 | CW | | 120 | 4.0 | 29 | | | | | | | | | | | | | | | | | | |
| S1D BP phex | Prod | 6 | 204 | 2.9 | 203 | 0.7 | 197 | | | | | | | | | | | | | | | | |
| S1D BP chex | Cons | 6 | 125 | 6.0 | 125 | | | | | | | | | | | | | | | | | | |
| S1D BP loss | Cons | 6 | 25 | 0.2 | 26 | | | | | | | | | | | | | | | | | | |
| S1D BP inj | Cons | 6 | 127 | 0.5 | 127 | | | | | | | | | | | | | | | | | | |

Table A.9 – Mean hot and cold stream data for Site Site R.

| Name | Type | P | $T_1$ | $Q_1$ | $T_2$ | $Q_2$ | $T_3$ | $Q_3$ | $T_4$ | $Q_4$ | $T_5$ | $Q_5$ | $T_6$ | $Q_6$ | $T_7$ | $Q_7$ | $T_8$ | $Q_8$ | $T_9$ | $Q_9$ | $T_{10}$ | $Q_{10}$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| S1D BP trac | Cons | 6 | 49 | 1.1 | 49 | | | | | | | | | | | | | | | | | |
| S1D MP loss | Cons | 6 | 25 | 0.3 | 26 | | | | | | | | | | | | | | | | | |
| S1D MP phex | Prod | 21 | 315 | 0.6 | 314 | 0.6 | 312 | 1.2 | 300 | 1.8 | 295 | 1.8 | 290 | | | | | | | | | |
| S1D MP chex | Cons | 21 | 125 | 0.9 | 130 | 0.9 | 135 | 1.8 | 145 | 1.4 | 150 | 0.9 | 160 | 1.4 | 165 | 0.9 | 170 | 0.9 | 180 | | | |
| S1D HP phex | Prod | 90 | 615 | 8.9 | 615 | | | | | | | | | | | | | | | | | |
| S1D VBP phex | Prod | 2 | 180 | 1.0 | 180 | | | | | | | | | | | | | | | | | |
| S1D VBP inj | Cons | 2 | 75 | 0.6 | 76 | | | | | | | | | | | | | | | | | |
| S1D VBP trac | Cons | 2 | 60 | 0.4 | 70 | 0.5 | 80 | 0.4 | 85 | | | | | | | | | | | | | |
| S1D AERO1 | Aero | | 130 | 2.2 | 45 | | | | | | | | | | | | | | | | | |
| S1D AERO1 bis | Aero | | 171 | 1.2 | 130 | | | | | | | | | | | | | | | | | |
| S1D AERO2 | Aero | | 138 | 2.8 | 60 | | | | | | | | | | | | | | | | | |
| S1D CW1 | CW | | 50 | 0.8 | 29 | | | | | | | | | | | | | | | | | |
| S1D CW2 | CW | | 79 | 8.2 | 45 | | | | | | | | | | | | | | | | | |
| S1E MP chex1 | Cons | 21 | 160 | 0.6 | 185 | 1.5 | 185 | 0.9 | 190 | | | | | | | | | | | | | |
| S1E MP losses | Cons | 21 | 25 | 0.7 | 26 | | | | | | | | | | | | | | | | | |
| S1E MP chex2 | Cons | 21 | 120 | 0.8 | 125 | 1.5 | 130 | 1.2 | 135 | 0.9 | 145 | 1.0 | 150 | 0.8 | 155 | 0.4 | 166 | 1.2 | 170 | | | |
| S1E BP chex1 | Cons | 6 | 110 | 1.8 | 110 | | | | | | | | | | | | | | | | | |
| S1E BP losses | Cons | 6 | 25 | 0.5 | 26 | | | | | | | | | | | | | | | | | |
| S1E BP chex2 | Cons | 6 | 90 | 0.6 | 92 | 1.1 | 93 | 1.7 | 95 | 2.0 | 97 | 0.3 | 100 | | | | | | | | | |
| S1E AERO1 | Aero | | 110 | 1.5 | 45 | | | | | | | | | | | | | | | | | |
| S1E AERO2 | Aero | | 114 | 2.3 | 45 | | | | | | | | | | | | | | | | | |
| S1E CW | CW | | 65 | 7.2 | 35 | | | | | | | | | | | | | | | | | |
| S1F BP phex | Prod | 6 | 218 | 1.8 | 217 | | | | | | | | | | | | | | | | | |
| S1F BP chex | Cons | 6 | 116 | 0.6 | 118 | 1.0 | 129 | 0.4 | 134 | | | | | | | | | | | | | |
| S1F BP loss | Cons | 6 | 25 | 0.7 | 26 | | | | | | | | | | | | | | | | | |
| S1F BP other | Cons | 6 | 130 | 0.8 | 130 | | | | | | | | | | | | | | | | | |
| S1F MP phex | Prod | 21 | 325 | 0.2 | 315 | 1.0 | 315 | 0.1 | 295 | | | | | | | | | | | | | |
| S1F MP loss | Prod | 21 | 25 | 0.5 | 26 | | | | | | | | | | | | | | | | | |
| S1F MP chex2 | Cons | 21 | 160 | 1.1 | 185 | 2.3 | 185 | 1.1 | 190 | | | | | | | | | | | | | |
| S1F CW1 | CW | | 73 | 7.3 | 44 | | | | | | | | | | | | | | | | | |
| S1F CW2 | CW | | 99 | 0.9 | 35 | | | | | | | | | | | | | | | | | |
| S1F CW3 | CW | | 104 | 2.7 | 48 | | | | | | | | | | | | | | | | | |
| S1F CW4 | CW | | 93 | 1.5 | 29 | | | | | | | | | | | | | | | | | |
| S1U MP trac | Cons | 21 | 160 | 4.5 | 180 | 8.9 | 180 | 4.5 | 190 | | | | | | | | | | | | | |
| S1U BP trac | Cons | 6 | 70 | 3.7 | 70 | | | | | | | | | | | | | | | | | |
| S1U1 MP trac | Cons | 21 | 160 | 0.9 | 180 | 1.8 | 180 | 0.9 | 190 | | | | | | | | | | | | | |
| S1U1 BP trac | Cons | 6 | 60 | 6.9 | 60 | | | | | | | | | | | | | | | | | |
| S1LOSSES BP | Cons | 6 | 25 | 2.9 | 26 | | | | | | | | | | | | | | | | | |
| S1LOSSES MP | Cons | 6 | 25 | 4.2 | 26 | | | | | | | | | | | | | | | | | |
| S1U PREMP | Cons | 21 | 110 | 3.1 | 150 | | | | | | | | | | | | | | | | | |
| S1U PREBP | Cons | 6 | 25 | 2.3 | 110 | | | | | | | | | | | | | | | | | |
| S1U DEGAZ | Cons | 6 | 145 | 11.4 | 145 | | | | | | | | | | | | | | | | | |

Table A.10 – Mean turbine properties for Site R.

| Name | $P_{in}$ [barg] | $P_{out}$ [barg] | $\eta[-]$ | Steam load $[t/h]$ | Power [MW] |
|---|---|---|---|---|---|
| S1 SHP HHP TURMP1 | 90.2 | 21.0 | 0.76 | 84.4 | 6.79 |
| S1 SHP HHP TURMP2 | 90.2 | 21.0 | 0.41 | 36.6 | 2.92 |
| S1 SMP HMP TURUTILS | 21.0 | 6.1 | 0.35 | 26.8 | 0.63 |
| S1A MP turb | 21.0 | 6.1 | 0.30 | 7.3 | 0.15 |
| S1C HP turb BP | 90.2 | 6.1 | 0.40 | 11.3 | 0.77 |
| S1C HP turb MP | 90.2 | 21.0 | 0.40 | 9.9 | 0.42 |
| S1D MP turb | 21.0 | 6.1 | 0.30 | 0.3 | 0.01 |

## A.2 Site P Process Units

All process requirements are defined using True Boiling Point definitions and are shown in Tables A.17 and A.18. For injections, the pressure of the columns are given. This pressure can be used to calculate the minimum injection pressure of the steam.

Turbine isentropic efficiencies are also supplied so as to calculate the steam cogeneration. Their overview is presented in Table A.19.

Losses are not considered inside the process units of Site P.

### Unit A - Cracker

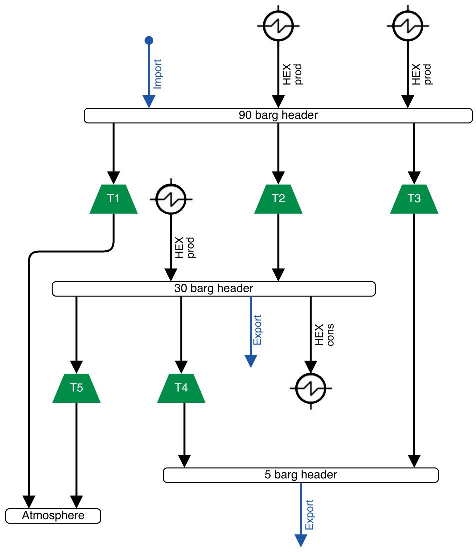



Figure A.7 – Schematic of the steam network of Site P Unit A.

Table A.11 – Steam, cooling demand and mean thermodynamic properties for Site P Unit A.

| Level [barg] | Type | Function | Flowrate [t/h] Mean | Flowrate [t/h] Max | Power [MW] Mean | Power [MW] Max | Process [°C] $T_{in}$ | Process [°C] $T_{out}$ | Column [barg] | $\eta$ [%] |
|---|---|---|---|---|---|---|---|---|---|---|
| 90 | Import | | -110.0 | -269.4 | -60.2 | -147.4 | | | | |
| 90 | HEX | Cooling | -76.6 | -95.0 | -41.9 | -52.0 | 550 | 500 | | |
| 90 | HEX | Cooling | -36.6 | -40.9 | -20.0 | -22.4 | 390 | 390 | | |
| 90 | Turbine T1 | | 81.8 | 104.7 | 44.7 | 57.3 | | | | 60.0 |
| 90 | Turbine T2 | | 112.6 | 259.3 | 61.6 | 141.8 | | | | 60.0 |
| 90 | Turbine T3 | | 28.8 | 31.5 | 15.7 | 17.2 | | | | 60.0 |
| | **Total cons.** | | **223.1** | **378.6** | **122.1** | **207.1** | | | | |
| 30 | HEX | Condensation | -36.6 | -92.7 | -20.1 | -51.0 | 280 | 260 | | |
| 30 | Export | | 57.0 | 126.5 | 31.4 | 69.6 | | | | |
| 30 | HEX | Evaporation | 94.1 | 99.8 | 51.8 | 54.9 | 180 | 180 | | |
| 30 | Turbine T4 | | 10.8 | 142.8 | 5.9 | 78.6 | | | | 60.0 |
| 30 | Turbine T5 | | 44.4 | 203.0 | 24.4 | 111.7 | | | | 60.0 |
| | **Total cons.** | | **206.3** | **422.0** | **113.4** | **232.1** | | | | |
| 5 | Export | | 39.5 | 172.0 | 23.8 | 103.7 | | | | |
| | **Total cons.** | | **0.0** | **0.0** | **0.0** | **0.0** | | | | |
| | Aero cooling | Cooling | | | 65.2 | 71.3 | 125 | 82 | | |
| | Water cooling | Cooling | | | 70.7 | 102.4 | 93 | 65 | | |

## Unit B – Butadien

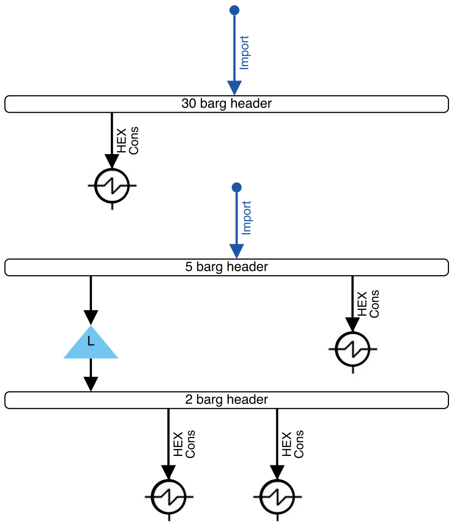



Figure A.8 – Schematic of the steam network of Site P Unit B.

Table A.12 – Steam, cooling demand and mean thermodynamic properties for Site P Unit B.

| Level [barg] | Type | Function | Flowrate [t/h] Mean | Max | Power [MW] Mean | Max | Process [°C] $T_{in}$ | $T_{out}$ | Column [barg] | $\eta$ [%] |
|---|---|---|---|---|---|---|---|---|---|---|
| 30 | Import | | -32.1 | -70.0 | -17.6 | -38.5 | | | | |
| 30 | HEX | Evaporation | 32.1 | 70.0 | 17.6 | 38.5 | 145 | 146 | | |
| | **Total cons.** | | **32.1** | **70.0** | **17.6** | **38.5** | | | | |
| 5 | Import | | -9.3 | -17.7 | -5.6 | -10.7 | | | | |
| 5 | HEX | Heating | 4.3 | 12.6 | 2.6 | 7.6 | 80 | 89 | | |
| 5 | Letdown | | 5.0 | 5.7 | 3.0 | 3.5 | | | | |
| | **Total cons.** | | **9.3** | **17.7** | **5.6** | **10.7** | | | | |
| 2 | HEX | Evaporation | 3.6 | 4.3 | 2.3 | 2.7 | 45 | 45 | | |
| 2 | HEX | Evaporation | 1.4 | 1.5 | 0.8 | 0.9 | 62 | 62 | | |
| | **Total cons.** | | **1.4** | **1.5** | **0.8** | **0.9** | | | | |
| | Aero cooling | Cooling | | | 4.0 | 4.6 | 135 | 88 | | |
| | Water cooling | Cooling | | | 22.3 | 26.9 | 110 | 45 | | |

### Unit C – Aromatics

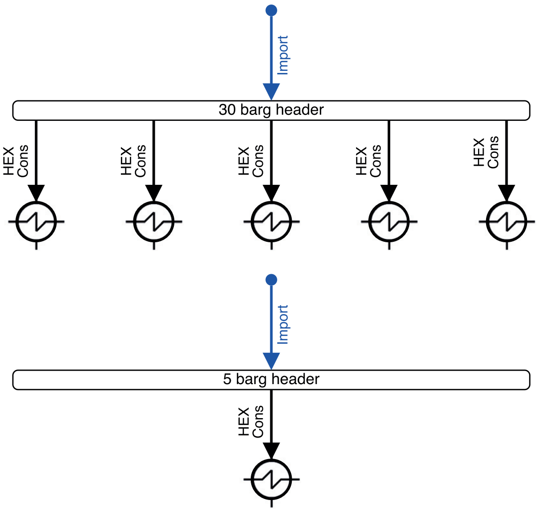



Figure A.9 – Schematic of the steam network of Site P Unit C.

Table A.13 – Steam, cooling demand and mean thermodynamic properties for Site P Unit C.

| Level [barg] | Type | Function | Flowrate [t/h] Mean | Flowrate [t/h] Max | Power [MW] Mean | Power [MW] Max | Process [°C] $T_{in}$ | Process [°C] $T_{out}$ | Column [barg] | $\eta$ [%] |
|---|---|---|---|---|---|---|---|---|---|---|
| 30 | Import | | -60.5 | -93.3 | -33.3 | -51.3 | | | | |
| 30 | HEX | Evaporation | 19.8 | 21.0 | 10.9 | 11.6 | 162 | 162 | | |
| 30 | HEX | Evaporation | 1.1 | 1.4 | 0.6 | 0.8 | 170 | 170 | | |
| 30 | HEX | Evaporation | 3.6 | 3.9 | 2.0 | 2.1 | 200 | 200 | | |
| 30 | HEX | Evaporation | 11.0 | 12.2 | 6.0 | 6.7 | 125 | 125 | | |
| 30 | HEX | Evaporation | 25.0 | 56.2 | 13.7 | 30.9 | 142 | 142 | | |
| | **Total cons.** | | **60.5** | **93.3** | **33.3** | **51.3** | | | | |
| 5 | Import | | -12.8 | -21.8 | -7.7 | -13.1 | | | | |
| 5 | HEX | Evaporation | 12.8 | 21.8 | 7.7 | 13.1 | 120 | 120 | | |
| | **Total cons.** | | **12.8** | **21.8** | **7.7** | **13.1** | | | | |
| | Aero cooling | Cooling | | | 19.2 | 24.2 | 135 | 45 | | |
| | Water cooling | Cooling | | | 3.9 | 5.4 | 110 | 40 | | |

## Unit D - Polymerisation

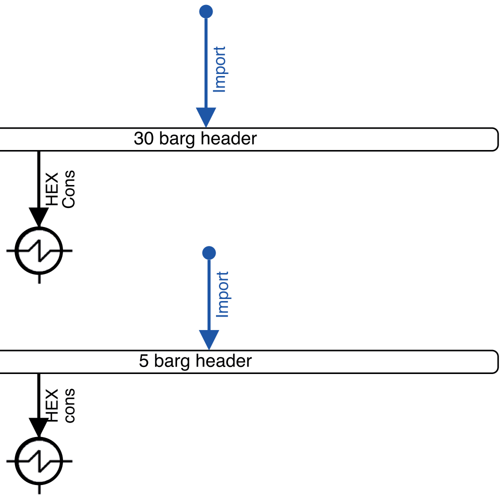



Figure A.10 – Schematic of the steam network of Site P Unit D.

Table A.14 – Steam, cooling demand and mean thermodynamic properties for Site P Unit D.

| Level [barg] | Type | Function | Flowrate [t/h] Mean | Flowrate [t/h] Max | Power [MW] Mean | Power [MW] Max | Process [°C] $T_{in}$ | Process [°C] $T_{out}$ | Column [barg] | $\eta$ [%] |
|---|---|---|---|---|---|---|---|---|---|---|
| 30 | Import | | -7.9 | -13.2 | -4.3 | -7.3 | | | | |
| 30 | HEX | Heating | 7.9 | 13.2 | 4.3 | 7.3 | 120 | 178 | | |
| | **Total cons.** | | **7.9** | **13.2** | **4.3** | **7.3** | | | | |
| | Water cooling | Cooling | | | 7.1 | 7.7 | NaN | NaN | | |

## Unit E – Oxidation

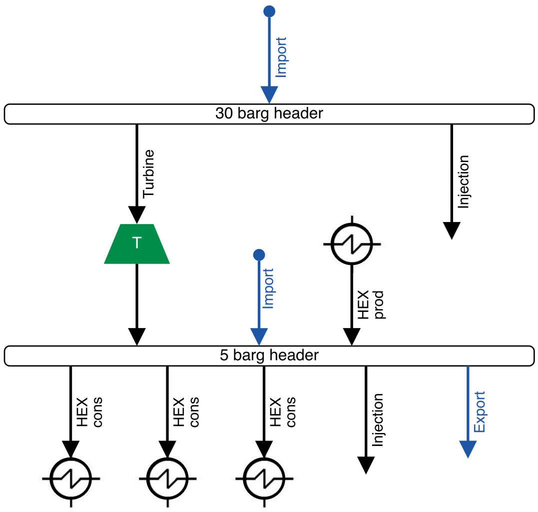



Figure A.11 – Schematic of the steam network of Site P Unit E.

Table A.15 – Steam, cooling demand and mean thermodynamic properties for Site P Unit E.

| Level [barg] | Type | Function | Flowrate [t/h] Mean | Flowrate [t/h] Max | Power [MW] Mean | Power [MW] Max | Process [°C] $T_{in}$ | Process [°C] $T_{out}$ | Column [barg] | $\eta$ [%] |
|---|---|---|---|---|---|---|---|---|---|---|
| 30 | Import | | -45.3 | -68.4 | -24.9 | -37.6 | | | | |
| 30 | Turbine | Turbo pumps | 41.0 | 61.8 | 22.5 | 34.0 | | | | |
| 30 | Injection | | 4.3 | 6.6 | 2.4 | 3.7 | | | 2.6 | |
| | **Total cons.** | | **45.3** | **68.4** | **24.9** | **37.6** | | | | |
| 5 | HEX | Process cooling | -15.5 | -32.8 | -9.3 | -19.8 | 230 | 189 | | |
| 5 | Import | | 29.7 | 54.0 | 17.9 | 32.6 | | | | |
| 5 | HEX | Process evaporation | 1.7 | 2.1 | 1.0 | 1.3 | 115 | 120 | | |
| 5 | HEX | Process evaporation | 2.4 | 3.0 | 1.4 | 1.8 | 50 | 55 | | |
| 5 | HEX | Process heating | 10.5 | 43.4 | 6.4 | 26.2 | 42 | 110 | | |
| 5 | Injection | | 12.2 | 16.0 | 7.3 | 9.7 | | | 1.3 | |
| | **Total cons.** | | **56.4** | **79.5** | **34.0** | **48.0** | | | | |
| | Aero cooling | Cooling | | | 2.9 | 4.2 | 180 | 92 | | |
| | Water cooling | Cooling | | | 11.6 | 14.9 | 130 | 65 | | |

## Unit F – Polymerisation

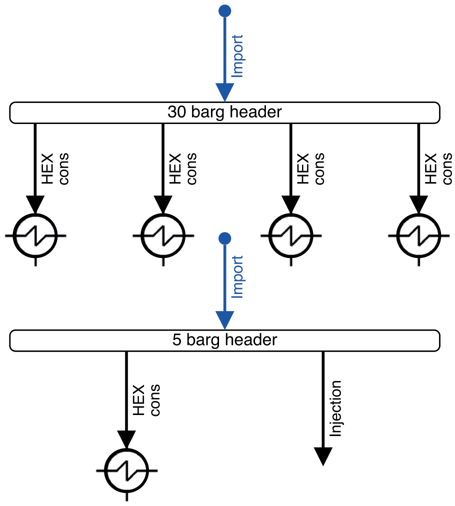



Figure A.12 – Schematic of the steam network of Site P Unit F.

Table A.16 – Steam, cooling demand and mean thermodynamic properties for Site P Unit F.

| Level [barg] | Type | Function | Flowrate [t/h] Mean | Flowrate [t/h] Max | Power [MW] Mean | Power [MW] Max | Process [°C] $T_{in}$ | Process [°C] $T_{out}$ | Column [barg] | $\eta$ [%] |
|---|---|---|---|---|---|---|---|---|---|---|
| 30 | Import | | -18.0 | -24.8 | -9.9 | -13.7 | | | | |
| 30 | HEX | Evaporation | 9.9 | 14.3 | 5.5 | 7.9 | 155 | 155 | | |
| 30 | HEX | Evaporation | 0.7 | 1.1 | 0.4 | 0.6 | 175 | 175 | | |
| 30 | HEX | Evaporation | 5.7 | 8.3 | 3.2 | 4.5 | 165 | 165 | | |
| 30 | HEX | Evaporation | 1.6 | 3.3 | 0.9 | 1.8 | 145 | 145 | | |
| | **Total cons.** | | **18.0** | **24.8** | **9.9** | **13.7** | | | | |
| 5 | Import | | -27.2 | -34.9 | -16.4 | -21.1 | | | | |
| 5 | HEX | Evaporation | 2.6 | 4.6 | 1.6 | 2.8 | 80 | 80 | | |
| 5 | Injection | | 24.6 | 32.4 | 14.9 | 19.6 | | | 0.5 | |
| | **Total cons.** | | **27.2** | **34.9** | **16.4** | **21.1** | | | | |
| | Water cooling | Cooling | | | 21.7 | 24.0 | 130 | 65 | | |

Table A.17 – Mean hot and cold stream data for Site Site P.

| Name | Type | P | $T_1$ | $Q_1$ | $T_2$ | $Q_2$ | $T_3$ | $Q_3$ | $T_4$ | $Q_4$ | $T_5$ | $Q_5$ | $T_6$ | $Q_6$ | $T_7$ | $Q_7$ | $T_8$ | $Q_8$ | $T_9$ | $Q_9$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| S2A HP phex | Prod | 90 | 550 | 31.1 | 550 | 31.1 | 500 | | | | | | | | | | | | | |
| S2A HP phex2 | Prod | 90 | 390 | 19.6 | 390 | | | | | | | | | | | | | | | |
| S2A MP chex | Cons | 30 | 180 | 46.0 | 180 | | | | | | | | | | | | | | | |
| S2A MP phex | Prod | 30 | 280 | 2.4 | 275 | 2.4 | 270 | 2.4 | 265 | 2.4 | 262 | 2.4 | 260 | | | | | | | |
| S2A AERO1 | Aero | | 175 | 15.0 | 130 | | | | | | | | | | | | | | | |
| S2A AERO2 | Aero | | 195 | 17.6 | 142 | | | | | | | | | | | | | | | |
| S2A AERO3 | Aero | | 160 | 26.7 | 120 | | | | | | | | | | | | | | | |
| S2A AERO4 | Aero | | 130 | 5.9 | 80 | | | | | | | | | | | | | | | |
| S2A CW1 | CW | | 90 | 24.0 | 60 | | | | | | | | | | | | | | | |
| S2A CW2 | CW | | 80 | 46.6 | 35 | | | | | | | | | | | | | | | |
| S2B MP chex | Cons | 30 | 145 | 17.6 | 146 | | | | | | | | | | | | | | | |
| S2B VBP chex1 | Cons | 2 | 45 | 2.2 | 45 | | | | | | | | | | | | | | | |
| S2B VBP chex2 | Cons | 2 | 62 | 0.8 | 62 | | | | | | | | | | | | | | | |
| S2B BP chex | Cons | 5 | 80 | 2.6 | 89 | | | | | | | | | | | | | | | |
| S2B AERO | Aero | | 98 | 4.0 | 45 | | | | | | | | | | | | | | | |
| S2B CW1 | CW | | 68 | 3.8 | 37 | | | | | | | | | | | | | | | |
| S2B CW2 | CW | | 47 | 5.4 | 47 | | | | | | | | | | | | | | | |
| S2B CW3 | CW | | 40 | 2.2 | 40 | | | | | | | | | | | | | | | |
| S2B CW4 | CW | | 57 | 4.9 | 57 | | | | | | | | | | | | | | | |
| S2B CW5 | CW | | 33 | 6.0 | 33 | | | | | | | | | | | | | | | |
| S2C MP chex1 | Cons | 30 | 162 | 10.6 | 162 | | | | | | | | | | | | | | | |
| S2C MP chex2 | Cons | 30 | 170 | 0.8 | 170 | | | | | | | | | | | | | | | |
| S2C MP chex3 | Cons | 30 | 200 | 2.0 | 200 | | | | | | | | | | | | | | | |
| S2C MP chex4 | Cons | 30 | 125 | 5.8 | 125 | | | | | | | | | | | | | | | |
| S2C MP chex5 | Cons | 30 | 142 | 14.0 | 142 | | | | | | | | | | | | | | | |
| S2C BP chex | Cons | 5 | 120 | 7.8 | 120 | | | | | | | | | | | | | | | |
| S2C AERO1 | Aero | | 90 | 4.8 | 70 | | | | | | | | | | | | | | | |
| S2C AERO2 | Aero | | 115 | 6.7 | 110 | | | | | | | | | | | | | | | |
| S2C AERO3 | Aero | | 100 | 3.8 | 97 | | | | | | | | | | | | | | | |
| S2C AERO4 | Aero | | 90 | 3.8 | 85 | | | | | | | | | | | | | | | |
| S2C CW2 | CW | | 70 | 2.7 | 65 | | | | | | | | | | | | | | | |
| S2C CW1 | CW | | 65 | 1.6 | 30 | | | | | | | | | | | | | | | |
| S2D MP chex | Cons | 30 | 120 | 0.9 | 135 | 0.9 | 150 | 0.9 | 155 | 0.9 | 161 | 0.9 | 178 | | | | | | | |
| S2D CW | CW | | 80 | 7.1 | 45 | | | | | | | | | | | | | | | |
| S2E inj | Cons | 30 | 140 | 2.4 | 140 | | | | | | | | | | | | | | | |
| S2E BP phex | Prod | 5 | 230 | 1.9 | 200 | 5.7 | 190 | 1.9 | 189 | | | | | | | | | | | |
| S2E BP inj | Cons | 5 | 125 | 2.0 | 125 | 2.0 | 130 | 2.7 | 135 | | | | | | | | | | | |
| S2E BP chex1 | Cons | 5 | 115 | 0.9 | 120 | | | | | | | | | | | | | | | |
| S2E BP chex2 | Cons | 5 | 50 | 1.7 | 55 | | | | | | | | | | | | | | | |

Table A.18 – Mean hot and cold stream data for Site Site P.

| Name | Type | P | $T_1$ | $Q_1$ | $T_2$ | $Q_2$ | $T_3$ | $Q_3$ | $T_4$ | $Q_4$ | $T_5$ | $Q_5$ | $T_6$ | $Q_6$ | $T_7$ | $Q_7$ | $T_8$ | $Q_8$ | $T_9$ | $Q_9$ | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| S2E BP chex3 | Cons | 5 | 42 | 6.9 | 110 | | | | | | | | | | | | | | | | |
| S2E AERO1 | Aero | | 130 | 1.9 | 110 | | | | | | | | | | | | | | | | |
| S2E AERO2 | Aero | | 110 | 0.5 | 100 | | | | | | | | | | | | | | | | |
| S2E AERO3 | Aero | | 145 | 0.5 | 142 | | | | | | | | | | | | | | | | |
| S2E CW | CW | | 100 | 11.6 | 90 | | | | | | | | | | | | | | | | |
| S2F MP chex1 | Cons | 30 | 155 | 5.4 | 160 | | | | | | | | | | | | | | | | |
| S2F MP chex2 | Cons | 30 | 175 | 0.4 | 175 | | | | | | | | | | | | | | | | |
| S2F MP chex3 | Cons | 30 | 165 | 3.2 | 165 | | | | | | | | | | | | | | | | |
| S2F MP chex4 | Cons | 30 | 145 | 0.9 | 145 | | | | | | | | | | | | | | | | |
| S2F BP inj | Cons | 5 | 125 | 14.9 | 125 | | | | | | | | | | | | | | | | |
| S2F BP chex | Cons | 5 | 80 | 1.6 | 80 | | | | | | | | | | | | | | | | |
| S2F AERO1 | Aero | | 115 | 16.2 | 113 | | | | | | | | | | | | | | | | |
| S2F AERO2 | Aero | | 110 | 6.7 | 105 | | | | | | | | | | | | | | | | |
| S2F AERO3 | Aero | | 105 | 4.0 | 90 | | | | | | | | | | | | | | | | |
| S2F CW1 | CW | | 90 | 9.8 | 70 | | | | | | | | | | | | | | | | |
| S2F CW2 | CW | | 70 | 11.9 | 35 | | | | | | | | | | | | | | | | |
| S2U MP | Cons | 30 | 90 | 1.9 | 95 | 0.9 | 100 | 1.4 | 105 | 0.2 | 110 | 1.0 | 115 | 0.5 | 120 | 0.6 | 125 | 1.7 | 130 | 0.6 | 135 |
| S2U BP | Cons | 5 | 65 | 2.0 | 70 | 2.8 | 75 | 0.4 | 80 | 3.8 | 85 | 0.5 | 90 | 3.3 | 95 | 2.6 | 100 | 0.8 | 105 | 0.9 | 110 |
| S2U1 MP | Cons | 30 | 90 | 0.1 | 95 | 0.0 | 100 | 0.1 | 105 | 0.0 | 110 | 0.1 | 115 | 0.0 | 120 | 0.0 | 125 | 0.1 | 130 | 0.0 | 135 |
| S2U1 BP | Cons | 5 | 65 | 1.5 | 70 | 0.6 | 75 | 1.8 | 80 | 0.4 | 85 | 0.7 | 90 | 1.2 | 95 | 0.3 | 100 | 1.3 | 105 | 0.9 | 110 |
| S2U2 MP | Cons | 30 | 100 | 0.4 | 105 | 0.2 | 110 | 0.3 | 115 | 0.1 | 120 | 0.2 | 125 | 0.1 | 130 | 0.1 | 135 | 0.4 | 140 | 0.1 | 145 |
| S2U2 BP | Cons | 5 | 90 | 1.8 | 95 | 0.6 | 100 | 0.6 | 105 | 0.6 | 110 | 0.3 | 115 | 0.8 | 120 | 1.9 | 125 | 0.5 | 130 | 1.2 | 135 |
| S2LOSSES BP | Cons | 5 | 25 | 2.3 | 26 | | | | | | | | | | | | | | | | |
| S2LOSSES MP | Cons | 5 | 25 | 6.0 | 26 | | | | | | | | | | | | | | | | |
| S2U PREMP | Cons | 30 | 110 | 2.8 | 150 | | | | | | | | | | | | | | | | |
| S2U PREBP | Cons | 5 | 25 | 3.8 | 110 | | | | | | | | | | | | | | | | |
| S2U DEGAZ | Cons | 5 | 120 | 12.3 | 120 | 1.4 | 145 | | | | | | | | | | | | | | |

Table A.19 – Mean turbine properties for Site P.

| Name | $P_{in}$ [barg] | $P_{out}$ [barg] | $\eta[-]$ | Steam load $[t/h]$ | Power [MW] |
|---|---|---|---|---|---|
| S2A HP turb1 | 90.0 | –0.9 | 0.60 | 73.6 | 14.78 |
| S2A HP turb2 | 90.0 | 30.1 | 0.60 | 122.7 | 5.90 |
| S2A HP turb3 | 90.0 | 5.0 | 0.60 | 27.9 | 2.89 |
| S2A MP turb4 | 30.1 | 5.0 | 0.60 | 11.6 | 0.65 |
| S2A MP turb5 | 30.1 | –0.9 | 0.60 | 46.5 | 7.13 |
| S2E turb | 30.1 | 5.0 | 0.40 | 41.0 | 1.53 |
| S2TUR MP | 90.0 | 30.1 | 0.71 | 104.1 | 5.93 |
| S2TUR BP | 90.0 | 5.0 | 0.60 | 45.9 | 4.92 |
| S2TURUTILS | 30.1 | 5.0 | 0.35 | 4.7 | 0.15 |

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# Stéphane L. Bungener

**Energy Systems & Audits**

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## Education

| | |
|---|---|
| **EPFL** | **Swiss Federal Institute of Technology Lausanne** |
| 05.2012 – Present | PhD in Energy Doctoral School |
| 10.2009 – 04.2012 | Masters in Applied Physics, Minors in Energy (5.6/6) |
| 10.2006 – 07.2009 | Bachelors in Physics |
| **Previous** | Haiti, France, UK, Switzerland |

## Experience

**INEOS** — **Engineering projects** France, Germany, Belgium, UK

05.2012 – 01.2016

Leading of mandatory UK energy audits (ESOS) on 2 industrial sites (5 person team). Data collection, proposal of efficiency solutions, report preparation and presentation to management. Submitted to UK Gov.

Energy audits of 5 industrial sites for efficiency proposals (utility networks and process units). Engagement of management to communicate findings and define future detailed engineering projects.

Implementation of data reconciliation tools in utility stream measurement systems, leading to more accurate measures and accounting. Steam losses were rigorously calculated for the first time.

Supervision of 4 engineering internships in industrial sites.

**ESOS** — **Lead Assessor/Auditor Certification** London, UK

10.2015

Certification to lead UK mandatory energy assessments and audits (ESOS), delivered by the Energy Managers Association.

**ISO 50001** — **Certification on Energy Auditing** Ribecourt, France

01.2015

Training on ISO 50001 energy auditing requirements, by DNG VL.

**Veolia** — **Engineering internship** Lausanne, Switzerland

09.2011 – 04.2012

Design of least cost solutions for district heating investments for Cergy city.

**Logitech** — **Engineering internship** Vancouver, USA

08.2010 – 02.2011

Designed a prototype testing system for blind subjective evaluation of headphones. Secured 50k$ funding to develop a full scale testing system.

## PROJECTS

**PhD thesis** — **Energy efficiency in the chemical industry**

05.2012 – 05.2016

Development of pathways towards energy efficiency in the chemical industry: from data collection and reconciliation to generation and evaluation of engineering solution, using advanced optimisation tools. Supervision 5 master theses and 6 research projects.

Identified significant energy saving potential in industrial sites (often >50%) through valorisation of existing resources. Contribution of tools to the research group and open community.

**Master thesis** — **Optimised design of district energy systems**

09.2011 – 04.2012

Development and programing of algorithms to optimally design district energy systems while minimising costs. Use of mathematical optimisation (AMPL) and advanced engineering methods (Pinch Analysis).

**Research proj.** — **Design of optimised solar cells using carbon nanotubes**

09.2009 – 06.2010

Experimental design of dye sensitized solar cells using Carbon Nanotubes. Optimisation of the composite proportions and testing of the resulting efficiency.

## ADDITIONAL EXPERIENCE

**FEL-100 (WEC)** — **Future Energy Leaders Programme**

04.2016 – to date

A pro bono platform to engage 100 young professionals worldwide in activities and events to become the next generation of leaders in energy and its sustainability, organised by the UN accredited World Energy Council.

**EPFL** — **Disciplinary Commission**

07.2009 – 08.2012

Judge on internal EPFL disputes concerning students and ethics.

**FORUM EPFL** — **Administration & Logistics** Lausanne, Switzerland

11.2007 – 11.2009

Leading of an 18 person team to organise the largest Swiss recruitment forum (180 companies, 5k guests). Development of sound accounting procedures and budgeting (600k CHF). ISO 14001 certification of the organisation and event.

### OTHER

| | |
|---|---|
| 10.2011 | Festival of Thinkers, Abu Dhabi, UAE. |
| 04.2011 | McKinsey & Company Dive Workshop, Rome, Italy. |
| 09.2005 – 06.2007 | Class delegate. |

## SKILLS

| | |
|---|---|
| Informatics | Mathematical optimisation, Matlab, Python, LUA, Excel |

## LANGUAGES

| | |
|---|---|
| English | Native (C2) |
| French | Native (C2) |
| Créole (Haiti) | Fluent |
| Spanish | Intermediate speaking and comprehension (B2) |
| German | Beginner (A2) |